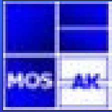
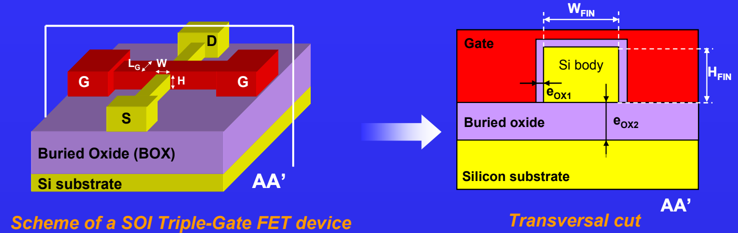
Modeling of the Subthreshold Characteristics of Triple-gate Transistors: Impact of the Channel Dimensions and Back-gate Bias



R. Ritzenthaler, F. Lime, and B. Iñiguez
Rovira I Virgili University (URV/ETSE)
26 Av. dels Països Catalans, 43007 Tarragona, Catalonia, Spain
Contact: romain.ritzenthaler@urv.cat

1. Context & motivations

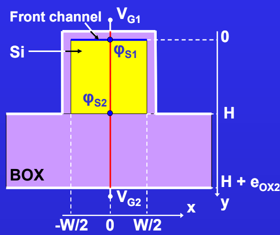
- Triple-gate devices [1][2]:
  - Candidates for further scaling of logic devices
  - Excellent subthreshold characteristics (I_{OFF}, SS, DIBL) control
- Assumptions:
  - Long channels
  - Undoped channels
  - Under the subthreshold regime (negligible carrier concentration)
  - Quantum confinement neglected (W & H > 10 nm)



Scheme of a SOI Triple-Gate FET device

Transversal cut

2. Solution of the Poisson's equation



- φ_{S1} considered constant along the top channel
- Front channel inversion corresponding to the threshold voltage of the whole device

- Truncation of the complete solution at the first order; unfitted model ($\lambda_2 = 2\sqrt{2}$) and fitted model (λ_2 depending on the geometrical dimensions):

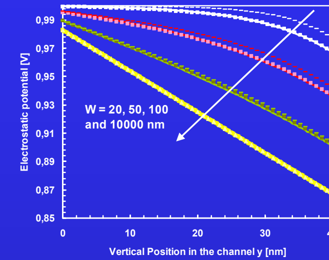
- potential in the vertical direction at the center of the device:

$$\varphi(y) = \varphi_{S1} + \frac{sh(y/\lambda_2)}{sh(H/\lambda_2)}(\varphi_{S2} - \varphi_{S1})$$

- Applying Gauss' theorem at the front and back interfaces yields:

$$V_{G1} = V_{FB1} + \varphi_{S1} + \frac{\varepsilon_{Si}}{C_{OX1}}\frac{1}{\lambda_2 sh(H/\lambda_2)}(\varphi_{S1} - \varphi_{S2})$$

$$V_{G2} = V_{FB2} + \varphi_{S2} + \frac{\varepsilon_{Si}}{C_{OX2}}\frac{1}{\lambda_2 th(H/\lambda_2)}(\varphi_{S2} - \varphi_{S1})$$



Comparison between Finite Elements solution (squares; obtained with [3]) and Fitted (plain lines)/ Unfitted (dashed lines) models

W\H [nm]	unfited	10	20	40	100
10	2√2	2	1,65	1,6	1,5
20	2√2	2,7	2,2	2	1,9
30	2√2	2√2	2,5	2,28	2,15
40	2√2	2√2	2,65	2,5	2,3
50	2√2	2√2	2,75	2,6	2,4
100	2√2	2√2	2,8	2,75	2,65
300	2√2	2√2	2√2	2√2	2,8
1000	2√2	2√2	2√2	2√2	2√2

Fit parameters α table ($\lambda_2 = W/\alpha$)

Potential modeled in the vertical direction

3. Threshold voltage model

- Considering the potentials when the back-gate is driven into inversion/depletion/accumulation, threshold voltage model derived [4,5]:

Back - gate into accumulation $\left(V_{G2} < V_{G2,ACC} = V_{FB2} - \frac{\varepsilon_{Si}}{C_{OX2}}\frac{\varphi_{ST}}{\lambda_2 th(H/\lambda_2)}\right)$:

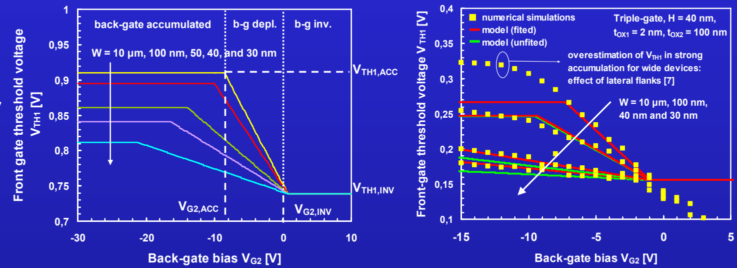
$$V_{TH1,ACC} = V_{FB1} + \frac{\varepsilon_{Si}}{C_{OX1}}\frac{\varphi_{ST}}{\lambda_2 sh(H/\lambda_2)}$$

Back - gate into depletion $(V_{G2,ACC} < V_{G2} < V_{G2,INV})$:

$$V_{TH1,DEP} = V_{FB1} - \frac{\frac{\varepsilon_{Si}}{C_{OX1}}\frac{1}{\lambda_2 th(H/\lambda_2)}}{1 + \frac{\varepsilon_{Si}}{C_{OX2}}\frac{1}{\lambda_2 sh(H/\lambda_2)}}(V_{G2} - V_{FB2}) + \left(1 + \frac{\varepsilon_{Si}}{C_{OX1}}\frac{1}{\lambda_2 th(H/\lambda_2)}\left(\frac{1}{1 + \frac{\varepsilon_{Si}}{C_{OX2}}\frac{1}{\lambda_2 sh(H/\lambda_2)}}\right)\right)\varphi_{ST}$$

Back - gate into inversion $(V_{G2} > V_{G2,INV} = V_{FB2} + \varphi_{ST})$:

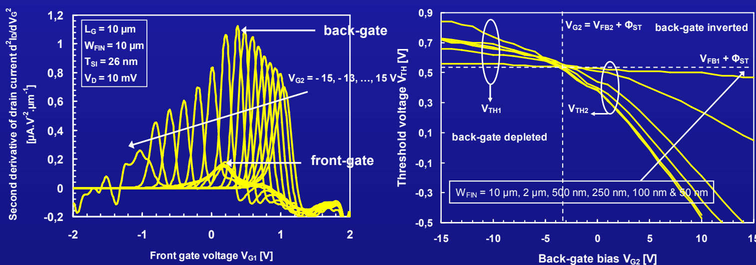
$$V_{TH1,INV} = V_{FB1} + {}_{ST}$$



Model of front gate threshold voltage V_{TH1} vs. back-gate bias V_{G2} for various fin width W

Comparison between numerical simulations (squares; obtained with [6]) and Fitted (red lines)/ Unfitted (green lines) models

Excellent accordance for fited model, correct for purely geometrical model



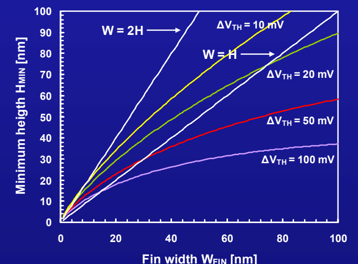
Simulated second derivative of the drain current vs. Back-gate bias V_{G2}. Two peaks in back-gate inversion appear

Experimental front gate threshold voltage V_{TH1} vs. back-gate bias V_{G2} for various fin width W (from [7])

Experimental existance of an invariant point between back-gate depletion and inversion regimes, marking the prior inversion of the front or the back-channel

- Considering the maximum amplitude (difference between the two plateaus):

$$H_{MIN}(W, \Delta V_{TH}) = \lambda_2 a\sinh\left(\frac{\varepsilon_{Si}\varphi_{ST}}{C_{OX1}\Delta V_{TH}}\frac{1}{\lambda_2}\right)$$



Minimum Fin height H vs. Fin width W for various ΔV_{TH}

For W < 2H, back-gate influence very significantly reduced

4. Conclusions

- Fully compact and versatile model for multi-gate transistors
- Accuracy adjustable with geometrical fit parameters
- Model validated by numerical simulations and experimental measurements
- Invariant point predicted by the model experimentally observed
- Definition of a geometrical criterion – if respected, the effect of the back-gate can be neglected

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