3-D Analytical Models for the Short-Channel Effect Parameters in Undoped FinFET Devices

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PURPOSE OF THE WORK

- Development of analytical scalable models of the FinFET subthreshold swing and threshold voltage based on a 3D electrostatic analysis of the FinFET structure
- The 3D basis of the model allows the expressions to inherently account for short-channel effects:
  - Subthreshold swing degradation
  - Threshold voltage roll-off
  - DIBL

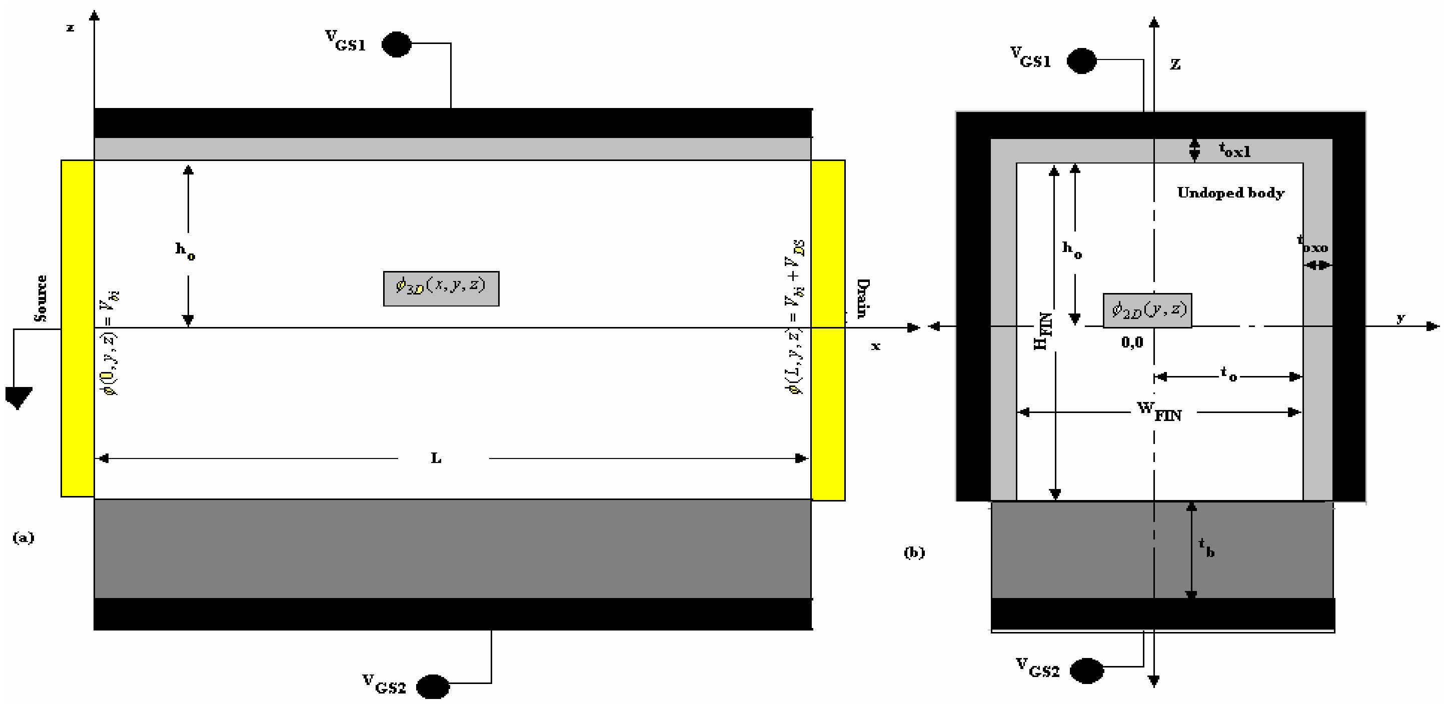
OUTLINE

- Introduction
- Electrostatic potential model derivation
- Subthreshold swing model
- Threshold voltage model
- Conclusions

INTRODUCTION

- The FinFET transistor is one of the most promising multi-gate MOS devices, due to:
  - excellent electrostatic control of the channel by the triple gate (which allows the device to be scaled down to several tens of nanometers of channel length)
  - relative simplicity of its process

INTRODUCTION



FinFET Cross section, a) xz- device structure, and b) yz-. device structure

INTRODUCTION

- Compact FinFET models are necessary for the design of future nanoscale CMOS circuits who will use FinFETs as transistors
- However, very few work on analytical modelling of FinFET characteristics has been done
- The reason of this lack of analytical work is probably related to the difficulty to model the 3D electrostatics of the device

INTRODUCTION

- In this work we present analytical models for the subthreshold swing and the threshold voltage of a FinFET
- The models are based on an analytical solution of the electrostatic potential, derived from the 3D Poisson's equation using adequate techniques
- Good agreement with numerical simulations and measurements have been found for channel lengths down to 30 nm

ELECTROSTATIC POTENTIAL MODEL

- The device electrostatics is governed by the 3D Poisson's equation:

$$\frac{\partial^2 \phi(x,y,z)}{\partial x^2} + \frac{\partial^2 \phi(x,y,z)}{\partial y^2} + \frac{\partial^2 \phi(x,y,z)}{\partial z^2} = \frac{q}{\varepsilon_{si}} n(x,y,z)$$

$$n(x,y,z) = n_i e^{\left[\phi(x,y,z) - \phi_F(x)\right]/V_T}$$

ϕ is the electrostatic potential

Boundary conditions for the quasi-Fermi potential:

$$\phi_F(0) = 0 \qquad \phi_F(L) = V_{ds}$$

ELECTROSTATIC POTENTIAL MODEL

- We consider that the electrostatic potential solution will be the sum of several components:

$$\phi(x,y,z) = \phi_{2D}(y,z) + \phi_{3D}(x,y,z)$$

  - Where $\phi_{2D}(y,z)$ is the 2D potential and related to 1D potential as

$$\phi_{2D}(y,z) = \phi_{1D}(y) + \alpha_o(y)\cdot z + \alpha_1(y)\cdot z^2$$

  - With boundary conditions

$$C_{ox1}\cdot\left[V_{GS1} - \phi_{ms} - \phi_{2D}(y, z = h_o)\right] = -\varepsilon_{Si}\left.\frac{\partial\phi_{2D}(y,z)}{\partial z}\right|_{z=h_0} \qquad C_{ox2}\cdot\left[V_{GS2} - \phi_{ms} - \phi_{2D}(y, z = -h_o)\right] = \varepsilon_{Si}\left.\frac{\partial\phi_{2D}(y,z)}{\partial z}\right|_{z=h_0}$$

  - V_{GS1} is the potential applied on both left/right and top gate and V_{GS2} is the potential applied on the bottom gate

ELECTROSTATIC POTENTIAL MODEL

- ϕ_{1D}(y) is the 1D potential solution:

$$\frac{\partial^2 \phi(y)}{\partial y^2} = \frac{q}{\varepsilon_{si}} n_i e^{\phi(y)/V_t}$$

- With boundary conditions:

$$\left.\frac{\partial \phi_{1D}(y)}{\partial y}\right|_{y=0} = 0 \qquad C_{oxo} \cdot \left[V_{GS1} - \phi_{ms} - \phi_{1D}(y = t_o)\right] = -\varepsilon_{si} \cdot \left.\frac{\partial \phi_0}{\partial y}\right|_{y=t_o}$$

- An analytical expression is found for ϕ_{1D}(y)

ELECTROSTATIC POTENTIAL MODEL

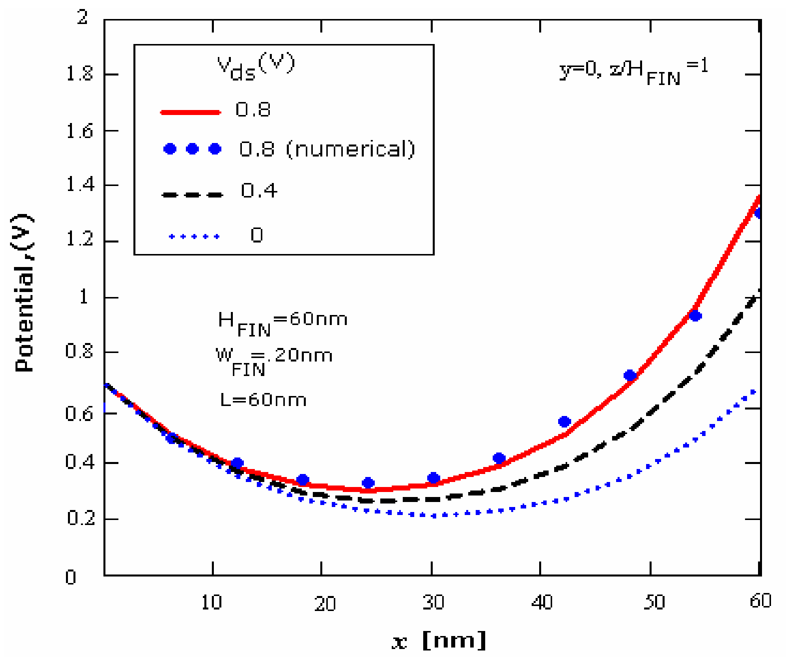
- The 3D potential component is the solution of the remaining 3D Laplace's equation with boundary conditions

$$C_{ox1} \cdot \left[0 - \phi_{3D}(x, y, z = h_o)\right] = -\varepsilon_{Si} \left.\frac{\partial \phi_{3D}(x, y, z)}{\partial z}\right|_{z=h_0} \qquad C_{ox2} \cdot \left[0 - \phi_{2D}(y, z = -h_o)\right] = \varepsilon_{Si} \left.\frac{\partial \phi_{3D}(x, y, z)}{\partial z}\right|_{z=h_0}$$

$$\phi_{3D}(0, y, z)\big| = V_{bi} - \phi_{2D}(y, z) \qquad \phi_{3D}(L, y, z)\big| = V_{DS} + V_{bi} - \phi_{2D}(y, z)$$

- An analytical expression is found for ϕ_{3D}
- The approximations used to obtain the analytical solution were to consider that:
  - ϕ_F is constant along the channel (which is valid in subthreshold) and equal to its value at the source end of the channel
  - the short-channel effects are not very severe, so that ϕ_{1D} is the dominant potential contribution for the electron charge density

ELECTROSTATIC POTENTIAL MODEL



ELECTROSTATIC POTENTIAL MODEL

- Using our analytical model for the electrostatic potential, we obtain an analytical expression of the location of the virtual cathode (the point along the channel where the potential is minimum, and therefore, of the minimum value ϕ_{min}
- The position of the virtual cathode will be instrumental to derive the subthreshold swing and threshold voltage expressions

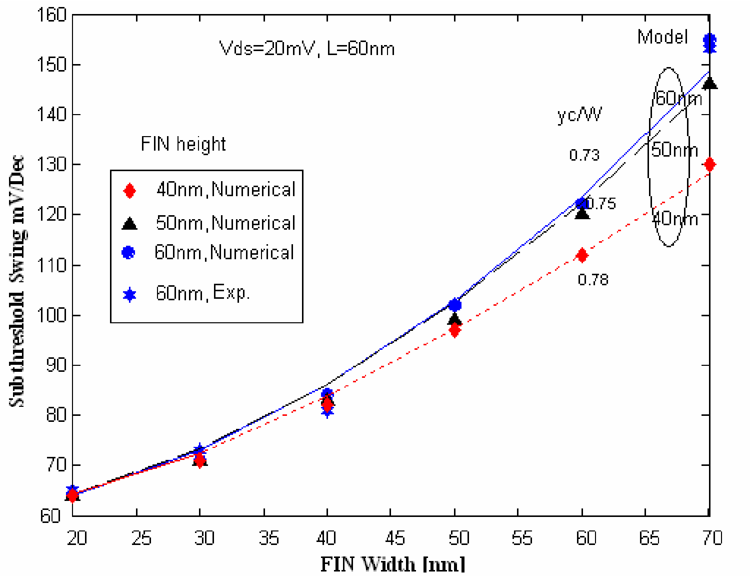
SUBTHRESHOLD SWING MODEL

- To obtain an expression of the subthreshold swing, we assume that the subthreshold drain current, I_D, is proportional to the total amount of free electrons diffusing over the virtual cathode:

$$S = \frac{\partial V_{GS}}{\partial \log I_D} = \left[\frac{2 \cdot \int_{z=-h_o}^{h_o} \int_{y=0}^{t_o} n_m(y,z) \frac{\partial \phi_{\min}(y,z)}{\partial V_{GS}} dydz}{2 \cdot \int_{z=-h_o}^{h_o} \int_{y=0}^{t_o} n_m(y,z) dydz} \right]^{-1} V_T \ln(10)$$

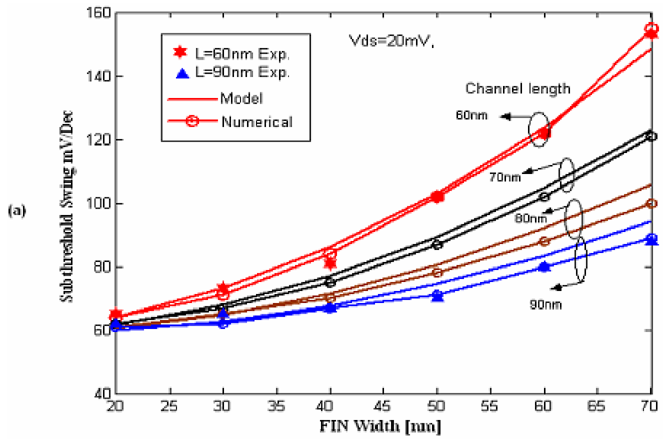
- An analytical expression is obtained solving the integrals by taking the values of the integrands at the conduction path (y_c, z_c)

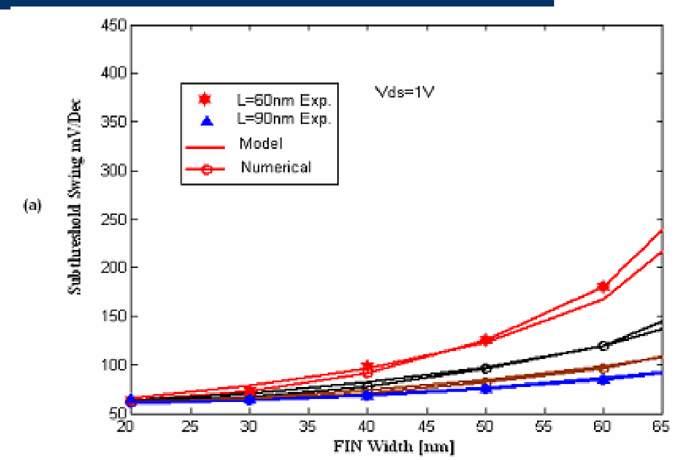
SUBTHRESHOLD SWING MODEL



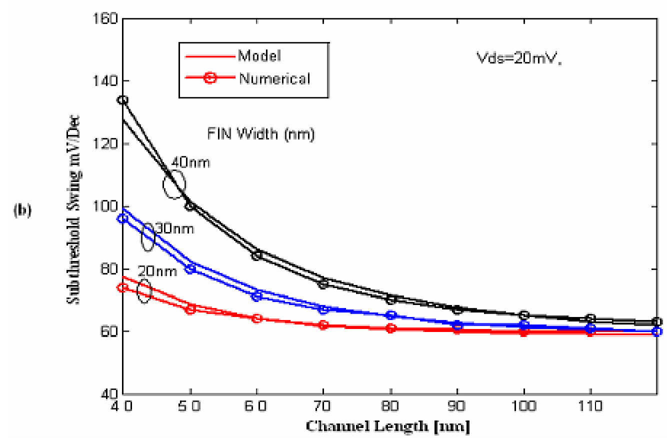
Good agreement with ·3D numerical simulations (DESSIS-ISE)
And experimental measurement (devices fabricated by IMEC, Belgium, and measured at UCL, Belgium)

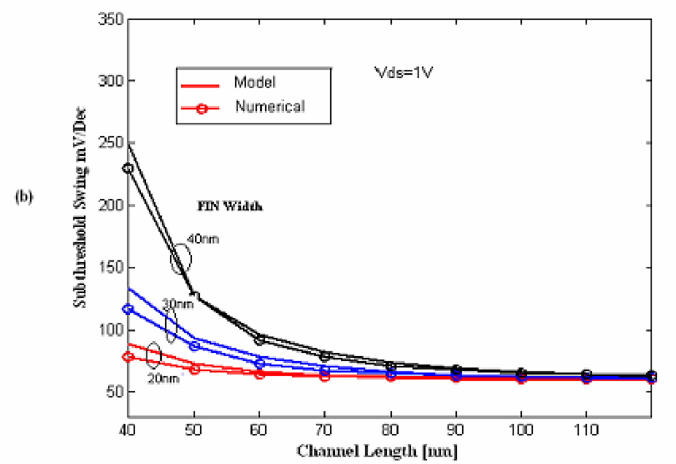
SUBTHRESHOLD SWING MODEL





H_{FIN}=60nm





THRESHOLD VOLTAGE MODEL

- The threshold voltage model is developed after defining it as the gate voltage necessary to reach a certain value of the mobile charge density per unit length Q_{TH}
- The mobile charge sheet density per unit length is obtained from:

$$Q_{inv} = 2\int_{y=0}^{t_o}\int_{z=-h_o}^{h_o} n_i \cdot e^{\frac{\phi_{min}(y,z)}{V_t}} dzdy$$

- We solve the last integral assuming that, in every half of the fin, its main contribution takes place at a location equal to $W_{fin}/4$: location of the conduction path along the fin width

THRESHOLD VOLTAGE MODEL

- We assume that the result of the integral along the z direction is equal to the value of the integrand at the location of the conduction path over an effective height equal to αH_{fin}, where α (≤ 1) is a correction factor which depends on H_{fin} and W_{fin}

$$Q_{inv} = n_i \cdot W_{FIN} \cdot \left(\alpha \cdot H_{FIN}\right) \cdot e^{\frac{\phi_{\min}(y_C, z_C)}{V_t}}$$

- The resulting expression of the threshold voltage, in terms of the threshold charge, is:

$$V_{TH} = \phi_{ms} + \frac{1}{1 - S_{gs}} \cdot \left(V_t \ln\left(\frac{Q_{TH}}{n_i \cdot W_{FIN} \cdot \alpha \cdot H_{FIN}} \right) - S_{ds} \right)$$

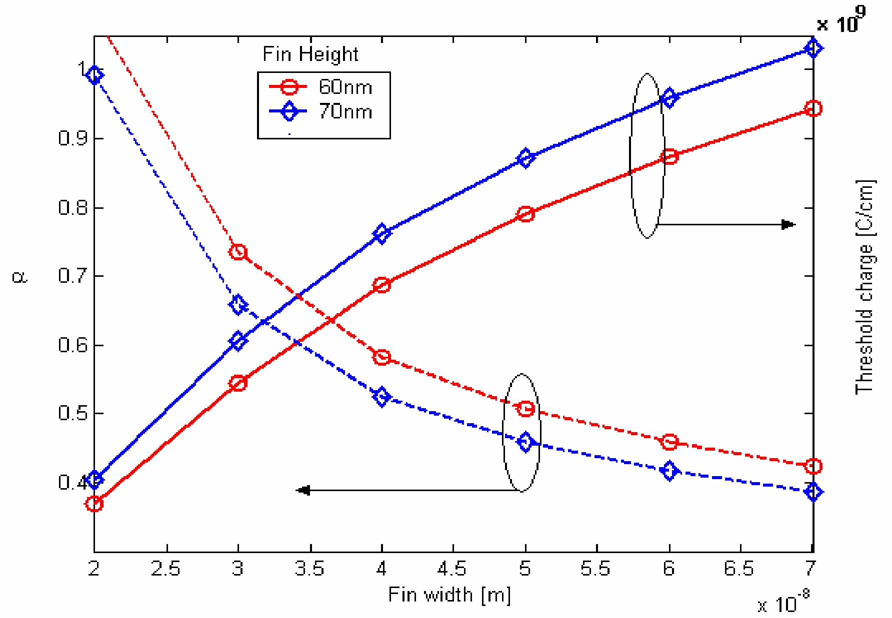
THRESHOLD VOLTAGE MODEL

- For long channel devices:

$$V_{TH} = \phi_{ms} + V_t \ln\left(\frac{Q_{TH}}{n_i \cdot W_{FIN} \cdot \alpha \cdot H_{FIN}}\right)$$

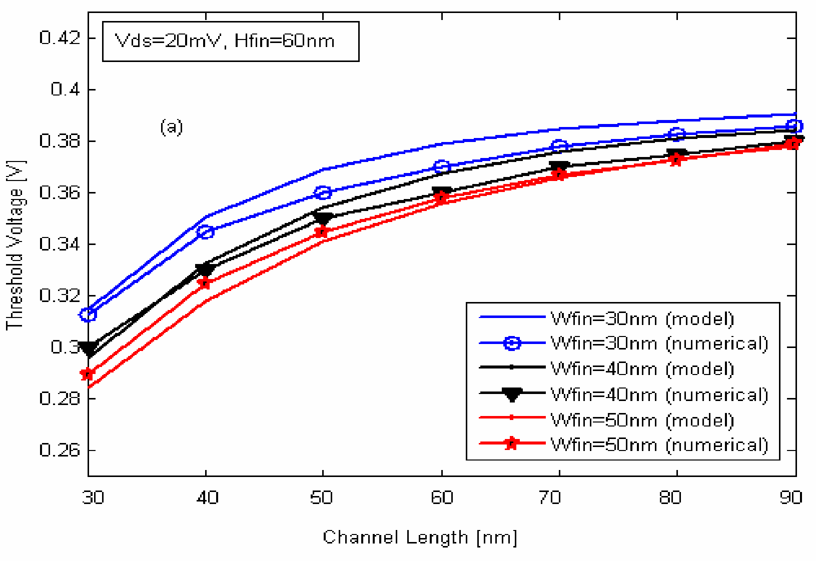
- In this FinFET threshold voltage model, the value of α makes it to tend to the DG MOSFET model for very large fin heights and to the square GAA MOSFET model for a symmetric device structure, as it should
- The value of Q_{TH} depends on the ratio W_{Fin}/H_{Fin}, for the dimensions of interest

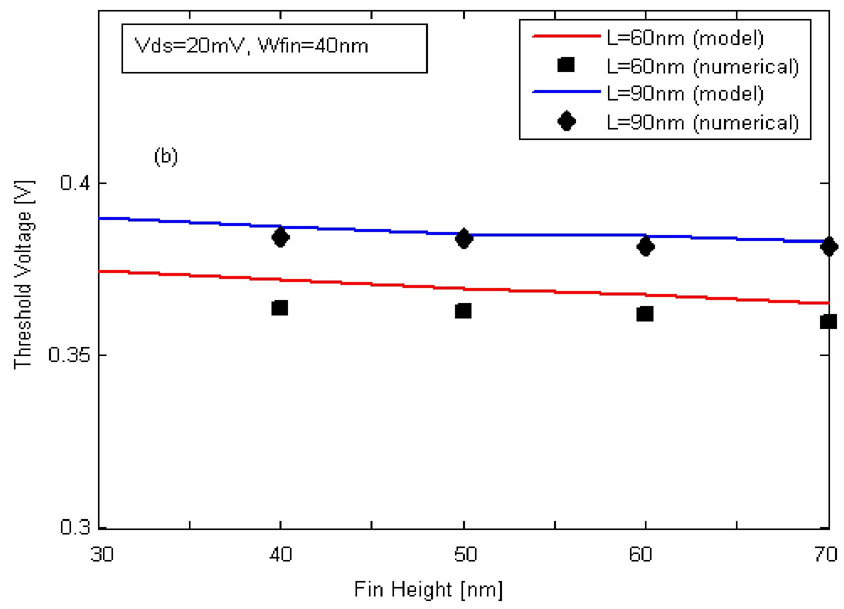
THRESHOLD VOLTAGE MODEL



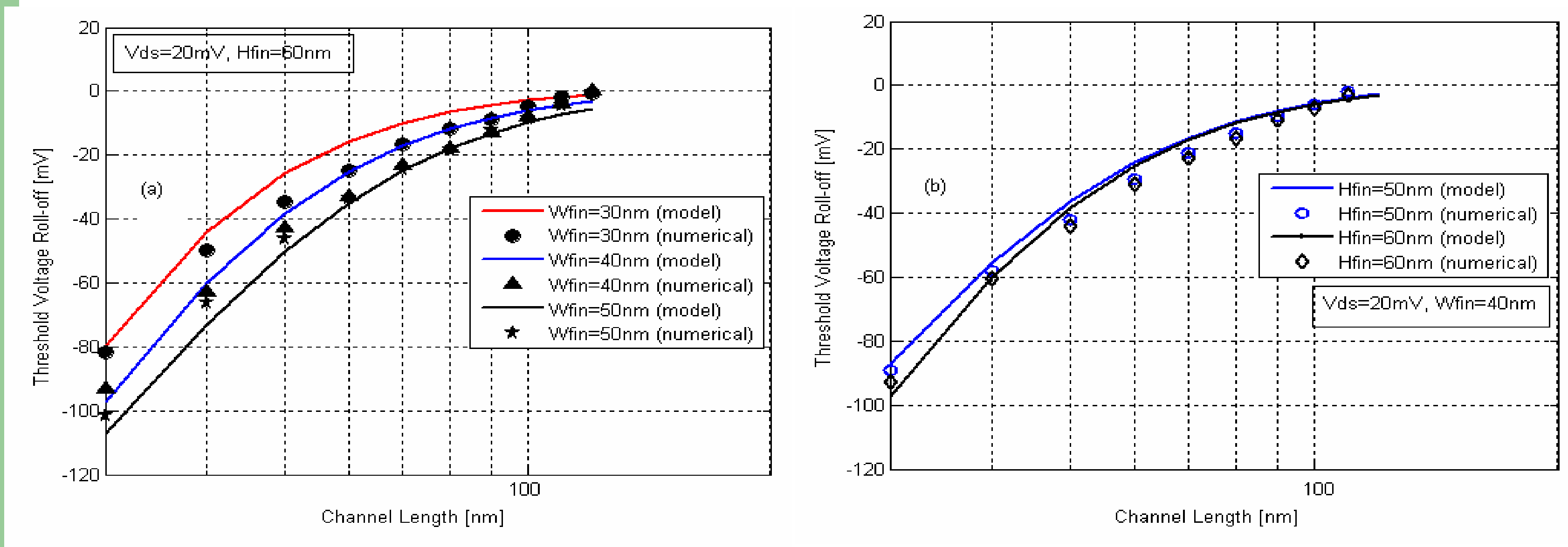
Extracted threshold charge value from long-channel threshold voltage model

THRESHOLD VOLTAGE MODEL



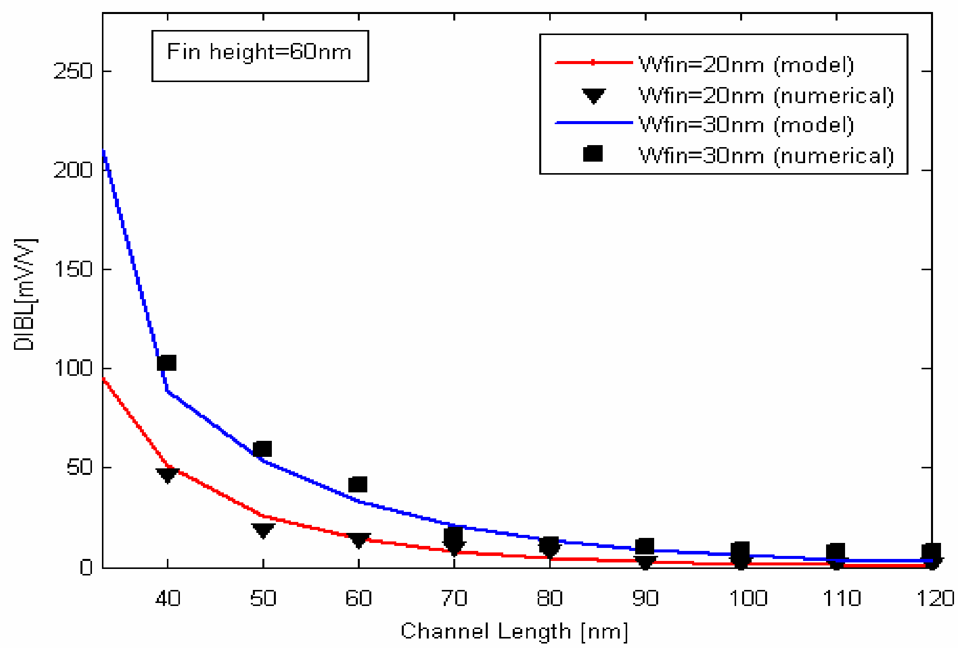


THRESHOLD VOLTAGE MODEL



Threshold voltage roll off

THRESHOLD VOLTAGE MODEL



DIBL coefficient

CONCLUSIONS

- We have developed analytical scalable models of the subthreshold swing and threshold voltage in FinFETs
- Our basis has been an approximate analytical solution of the 3D Poisson's equation, obtained using suitable techniques
- The short channel effects are inherently included in the models
- Very good agreement has been obtained with 3D numerical simulations (DESSIS-ISE) and experimental measurements for channel lengths down to 30 nm

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