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Physics-Based Scalable Threshold-Voltage Model for Strained-Silicon MOSFETs

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- **Abstract**

An analytical threshold-voltage (V_t) model derived from Poisson equation for NMOS devices with a strained-silicon channel is described in terms of band, material, doping, and structure parameters and validated with Medici simulations. The model equations are derived based on bulk reference to preserve the symmetry of the model, and extended to short-channel devices based on previously-developed bulk-Si V_t model.

- **Motivation**

Strained silicon MOSFETs have been receiving considerable attention owing to their potential for achieving higher performance and compatibility with conventional bulk silicon. This recent strong interest calls for the extension of conventional MOSFET modeling to this promising device.

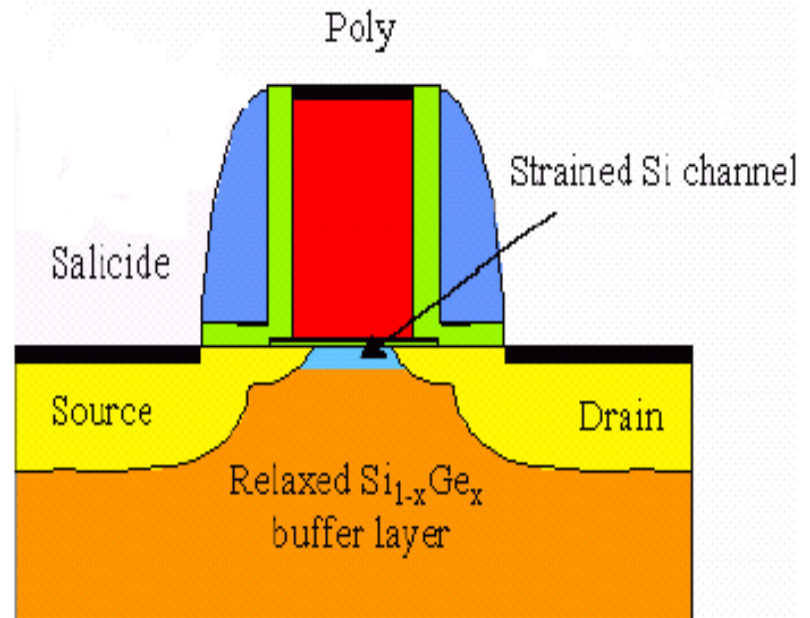
Strained-Silicon MOSFETs

With changes in the Ge mole fraction, the different parameters that change are:

- Band gap
- Conduction and valence band offsets
- Effective density of states and, hence, intrinsic concentration.
- Mobility

Strained-silicon parameters:

- Strained-silicon layer thickness
- Strained-silicon layer doping





Threshold voltage in strained silicon MOSFETs

- The strained-silicon MOSFET exhibits a shifted threshold voltage from conventional silicon devices due to the band offset at the heterojunction between the strained silicon and the SiGe layers.
- The silicon channel is very thin and usually small compared to the depletion width.
- For very small drain voltages and long-channel MOSFETs, an analysis can be carried out in one dimension, perpendicular to the surface. Poisson equation is solved for one-dimensional case.

Threshold voltage in strained silicon MOSFETs

The potential across the SiGe substrate can be written as

$$\phi_1(x) = \frac{qN_a x^2}{2\epsilon_{SiGe}} \quad (0 < x < x_d)$$

The potential across the strained-silicon layer can be written as

$$\phi_2(x) = \frac{qN_a x_d^2}{2\epsilon_{SiGe}} + \frac{qN_a t_{Si}^2}{2\epsilon_{SiGe}} + \frac{qN_a t_{Si} x_d}{\epsilon_{Si}} \quad (0 < x < t_{Si})$$

Depletion layer potential in the oxide can be written as

$$\phi_3(x) = \frac{qN_a x_d^2}{2\epsilon_{SiGe}} + \frac{qN_a t_{Si}^2}{2\epsilon_{SiGe}} + \frac{qN_a t_{Si} x_d}{\epsilon_{Si}} + \frac{qN_a t_{ox} (t_{Si} + x_d)}{\epsilon_{ox}} \quad (0 < x < t_{ox})$$

Threshold voltage in strained silicon MOSFETs

Since strong inversion occurs at the Si/SiO₂ interface, the threshold potential can be solved from

$$\phi_{th} = \phi_2(t_{Si})$$

where ϕ_{th} is given by the expression

$$\phi_{th} = \frac{2kT}{q} \ln\left(\frac{N_a}{n_i}\right) - \Delta E_c$$

The width of the depletion region in the SiGe substrate can be obtained as

$$x_d = \sqrt{t_{Si}^2 - \frac{\epsilon_{SiGe}}{\epsilon_{Si}} t_{Si}^2 + \frac{2\epsilon_{SiGe}}{qN_a} (\phi_{s0} - \Delta E_c) - t_{Si}}$$

The threshold voltage is obtained by substituting the boundary condition

$$V_t - V_{FB} = \phi_3(t_{ox})$$

Threshold voltage in strained silicon MOSFETs

The flat-band voltage is given by

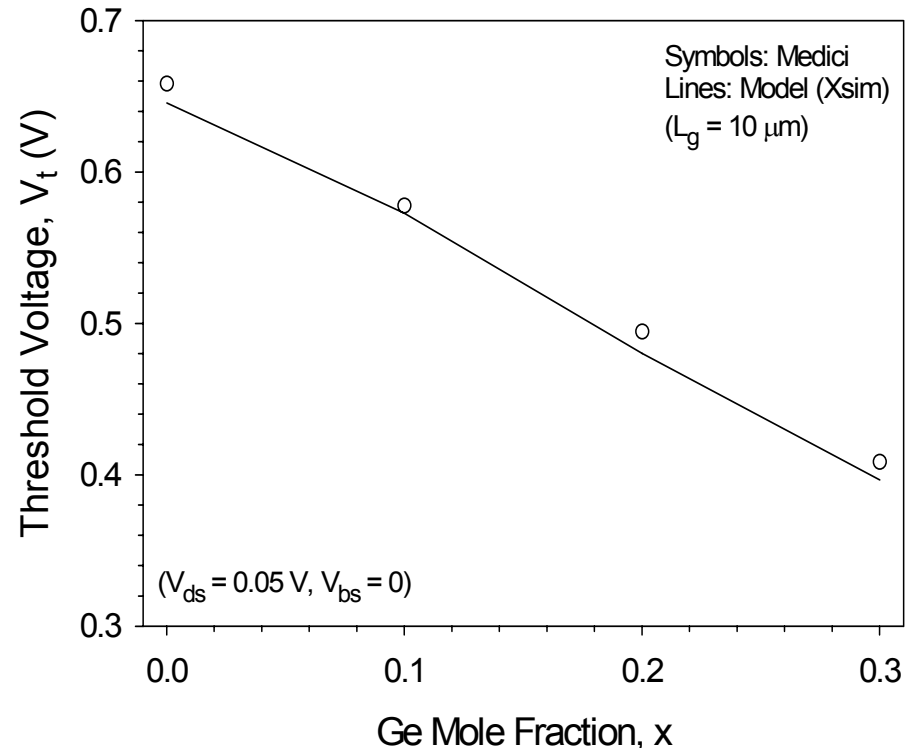
$$V_{FB} = \phi_m - \left(\chi + \frac{E_g}{2} + \phi_F \right) + \frac{qN_{atSi}}{C_{ox}} - \frac{qN_{atSi}^2}{2\epsilon_{Si}}$$

The long-channel linear threshold voltage (zero body bias) is given by

$$V_{t0} = V_{FB} + (\phi_{s0} - \Delta E_c) + \frac{qN_a(x_d + t_{Si})}{C_{ox}}$$

Threshold-voltage definition:

- Linear threshold voltage has been extracted at different gate lengths using the maximum- g_m method
- The threshold voltages for different substrate and drain biases have been extracted based on the constant-current definition* (* X. Zhou, K. Y. Lim, and W. Qian, *Solid-State Electron.*, vol. 45, pp. 507–510, 2001.)



Prediction of the linear threshold voltage for different Ge mole fractions.

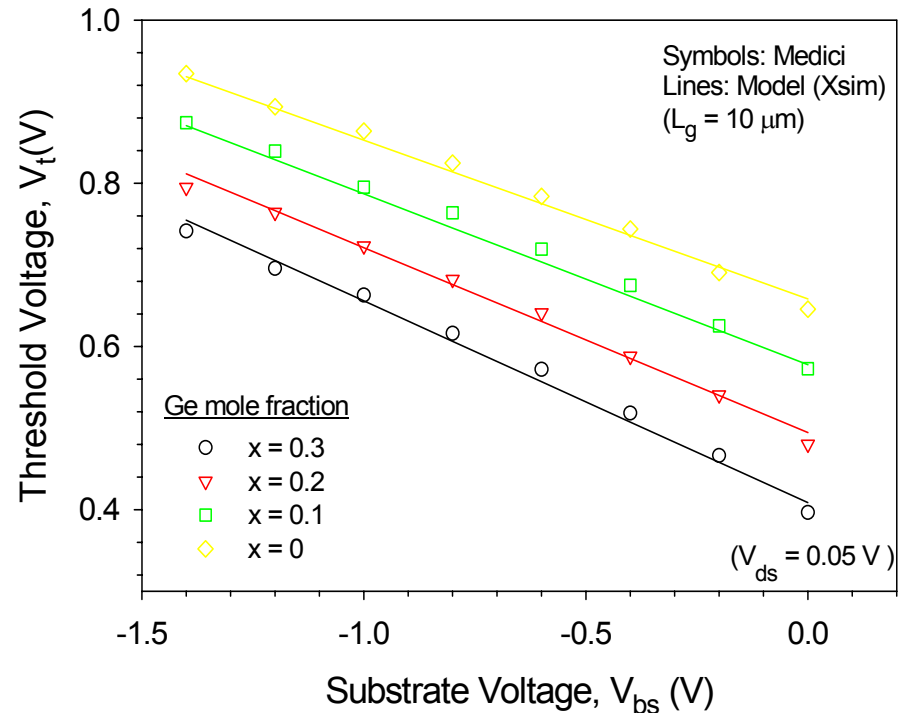
Symmetrical model

As bulk-referenced models are symmetric, continuous, and easy to handle in weak inversion and current saturation regions, the derivation is done based on bulk reference

$$V_t = V_{t0} - (A_b - 1)V_{bs}$$

$$A_b = 1 + \frac{\zeta \epsilon_{SiGe}}{C_{ox} \sqrt{t_{Si}^2 - \frac{\epsilon_{SiGe}}{\epsilon_{Si}} t_{Si}^2 + \frac{2\epsilon_{SiGe}}{qN_a} (\phi_{s0} - \Delta E_c)}}$$

where ζ is a fitting parameter introduced due to the Taylor series approximation



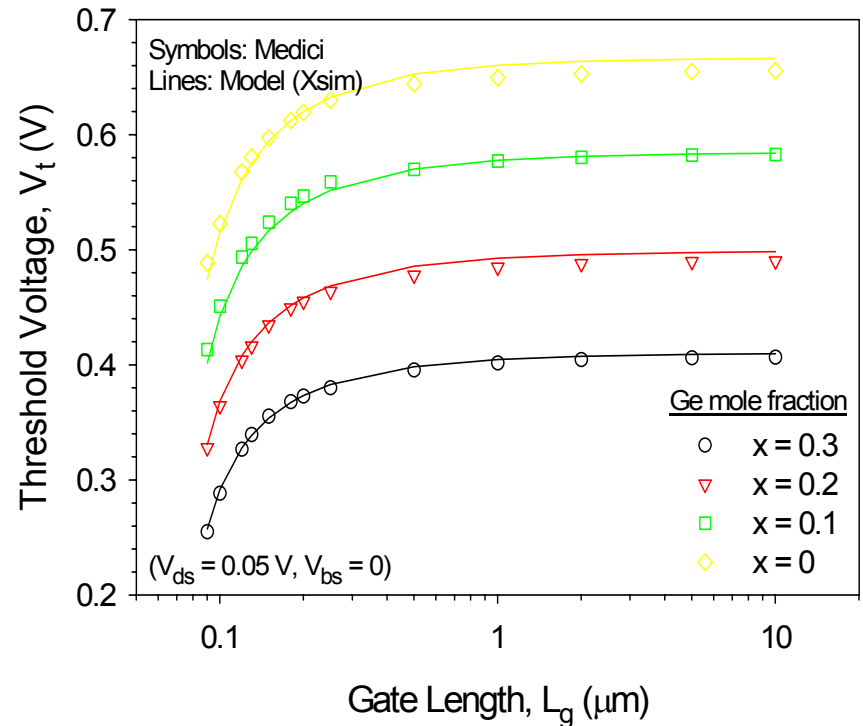
Prediction of the linear threshold voltage vs. substrate bias for different Ge mole fractions.

Short channel strained-silicon

V_t model

- The solution is extended to the two-dimensional case to account for the short-channel effects (SCEs)
- The general idea is to retain the simple one-dimensional form of the long-channel V_t equations while building the 2-D short-channel effects in the effective channel doping and surface potential*.

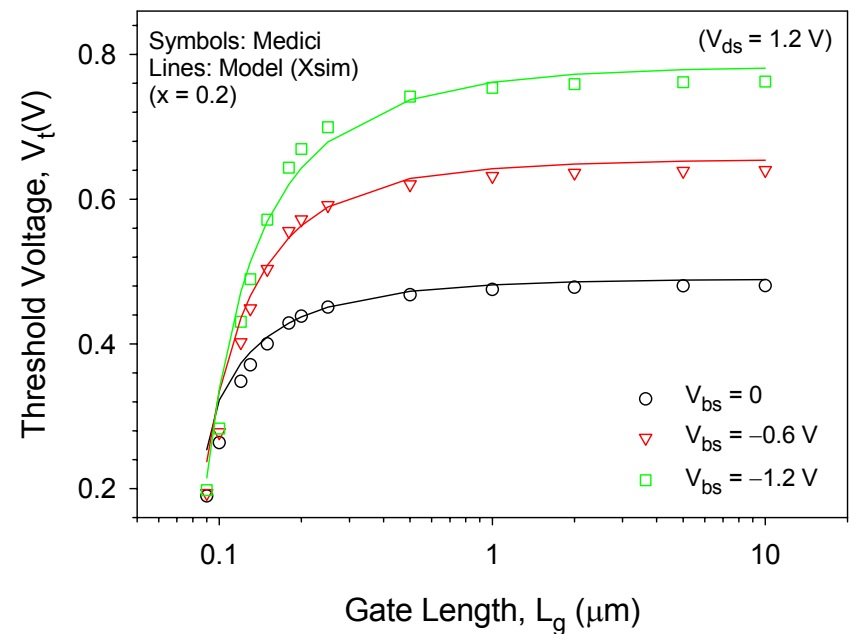
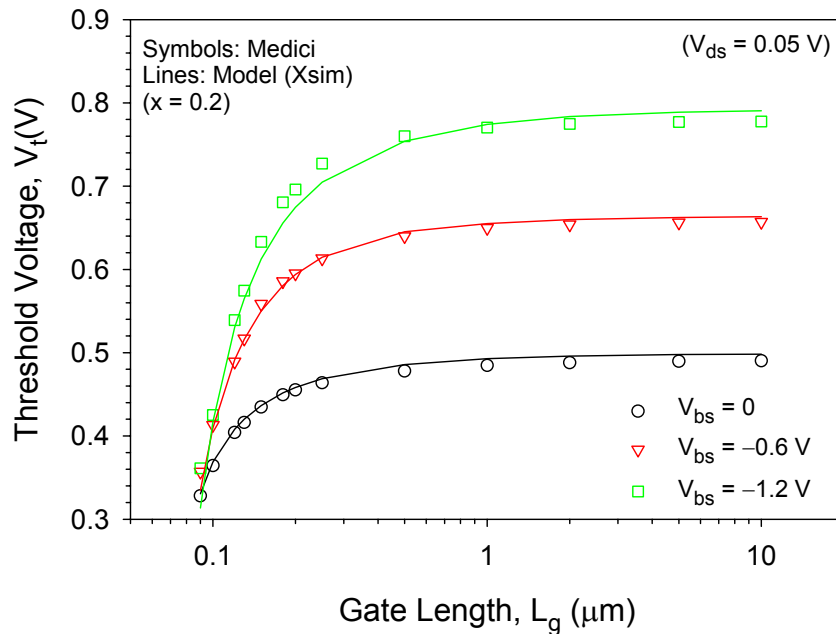
(* X. Zhou and K. Y. Lim, *IEEE Trans. on Electron Devices*, vol. 48, no. 5, pp. 887–896, 2001.)



Prediction of the linear threshold voltage vs. gate length for different Ge mole fractions.

Geometry and bias scalability

To extract the fitting parameters, our compact model uses a very simple, four-step, one-iteration extraction procedure, which requires the measured or simulated V_t vs. L_g data from the same process with only four sets measurements



Prediction of the V_t vs. L_g curve for a Ge mole fraction of 20% for different substrate biases at (a) $V_{ds} = 0.05$ V and (b) $V_{ds} = 1.2$ V.



Conclusion - Approach

- A one-dimensional Poisson equation is solved to determine the threshold-voltage shift with different Ge mole fractions.
- The SCEs on the threshold voltage of strained-silicon are modeled by porting the above strained-silicon long-channel V_t model to our previously-developed short-channel V_t model for bulk-silicon MOSFETs.
- A set of threshold voltages for different gate lengths and bias conditions are needed to calibrate the short-channel model.
- The strained-silicon V_t model converges to the bulk-silicon model when Ge mole fraction becomes zero.



Conclusion - Significance

- The model predicts the threshold-voltage shift with different Ge mole fractions and strained-silicon layer thickness and doping.
- The model equations have been derived based on the bulk reference to preserve the symmetry of the model.
- The calibrated model can be used to predict the threshold voltages at different gate lengths and terminal bias conditions for different Germanium mole fractions.
- The scalable strained-silicon V_t model will be used as the basis for bulk charge/capacitance modeling in accumulation/depletion regions.