



Surface Potential or Inversion Charge?

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Common Accomplishment of Several Modeling Groups

We have reached a consensus to move beyond

$$Q_{inv} = C(V_{gs} - V_{th})$$

$$I_{subth} = I_0 \exp[q(V_{gs} - V_{th} - V_{off})/nkT]$$

V_{th} = Sum of 12 terms with further improvements planned

It remains is to determine where to go from here

Dynamics of MOSFET Model Development (Personal View)

References can be found in a joint paper.

1. Original V_{th} -based and surface-potential-based models (**SPBMs**) were developed almost simultaneously. The first correct formulation of both is in C.T. Sah's 1960's papers.
 2. Compact **SPBMs** are considered as too complex and inefficient for practical use.
 3. V_{th} -based **BSIM3** becomes successful standard model with strong competition from other models
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Dynamics of MOSFET Model Development (cont.)

4. Between 1995 and 2002 it becomes clear that V_{th} -based approach has fundamental problems

Key development: advanced V_{th} -based models are no longer simpler than contemporary SPBMs.

5. Q_i -based models bridge the gap between the perceived complexity of SPBM and the actual insufficiency of V_{th} -based models.
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Dynamics of MOSFET Model Development (cont.)

5. Based on the new solutions of old problems **SPBMs** progress very rapidly. In many ways they become simpler than the original Brews' formulation
 7. Advanced **Q_i -based** models become more complex as compared to elegant originals. All three approaches to MOSFET modeling converge in terms of complexity.
 8. Since the physical content and flexibility of **SPBMs** is far higher, the window of opportunity for **Q_i -based and V_{th} -based** models is now closed.
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Comparison of Φ_s -Based and Q_I -Based Options

Pao-Sah eq. (Φ_s -based)

$$(V_{gb} - V_{fb} - \phi_s)^2 = \gamma^2 \phi_t \left[e^{-x} + x - 1 + \Delta_n (e^x - x - 1) \right]; \quad (1)$$

$$x = \phi_s / \phi_t, \Delta_n = \exp \left[-(2\phi_b + \phi_n) / \phi_t \right]$$

Drop the accumulation

$$\left[(V_{gb} - V_{fb} - \phi_s) / \gamma \right]^2 = \phi_s + \phi_t \Delta; \Delta = \exp \left[(\phi_s - 2\phi_b - \phi_n) / \phi_t \right] \quad (2)$$

Reformulate in terms of q_i, q_b

$$q_i + q_b + \phi_t \ln \left[q_i (q_i + 2q_b) / (\gamma^2 \phi_t) \right] = V_{gb} - V_{fb} - \phi_n - 2\phi_b \quad (3)$$

Further simplify, introduce variables n and n_1 with various physical interpretations and expressions

$$(q_i/n) + \phi_t \ln (q_i/n\phi_t) = (V_{gb} - V_{fb})/n - \phi_n - n_1 \quad (Q_i\text{-based}) \quad (4)$$

Example of How SPBM's Were Simplified

Original CSM (C.C. McAndrew and J. Victory, 2002)

$$Q_D = -\frac{q_{d1} + q_{d2} + q_{d3} + q_{d4} + q_{d5} + q_{d6} + q_{d7}}{\left(V_{gb} - V_{fb} - \overline{\varphi_c} - \gamma \overline{\varphi_c}^{-1/2}\right)^2 + \varepsilon}$$

$$q_{d1} = \left(V_{gb} - V_{fb}\right)^2 \left[\frac{V_{gb} - V_{fb}}{2} - \frac{4\varphi_s + 5\varphi_d}{6} - \frac{2\gamma}{15} \times \frac{7\varphi_s^{3/2} + 14\varphi_s\sqrt{\varphi_d} + 16\sqrt{\varphi_s}\varphi_d + 8\varphi_d^{3/2}}{\left(\sqrt{\varphi_s} + \sqrt{\varphi_d}\right)^2 + \varepsilon} \right]$$

...

SP or PSP

$$Q_D = \frac{1}{2} \left[q_{im} - \frac{\alpha_m \phi}{6} \left(1 - \frac{\phi}{2H} - \frac{\phi^2}{20H^2} \right) \right], \quad H = \phi_t + q_{im} / \alpha_m$$

Accumulation and Overlap Regions

There is no inversion charge there. Inversion charge-modes can deal with this problem by... **becoming SPBMs**. Why not do the right thing from the beginning and in all regions?

Tunneling

As tunneling currents become more important they need to be modeled more accurately. But Tsu-Esaki formula contains “supply function” that is not readily evaluated without surface potential. Once the latter is available the gate current modeling can be put within the usual framework of symmetric linearization.

What's Behind the Rapid Progress of SPBMs?

1. Equations for currents and charges have been rigorously simplified so that in **PSP** they are simpler than in V_{th} or Q_i -based models (or some other **SPBMs**)
 2. Computation of surface potential is extremely efficient (whether done iteratively or analytically)
 3. We've learned how to efficiently model small-geometry effects without V_{th} .
 4. NQS model available in **PSP** is, probably, superior to any other. No need for separate large-signal and transient NQS models
 5. In the S/D overlap regions computation of surface potential is especially easy. This enables more physical modeling of parasitics than ever.
 6. Mathematical techniques for including new device physics have been developed and verified.
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What about Multiple Gate MOSFETs?

1. The popular statement that **SPBMs** cannot model bulk inversion is wrong. It is based on confusing the approach based on surface potential approach with the special case of charge-sheet approximation.
 2. The fundamental device physics is still the control of the conductivity by the **surface potentials**.
 3. Schrodinger Equation contains **potentials**
 4. Transmission/reflection coefficients in the one-flux model of quasi-ballistic transport depends on the potential profile, not charge density.
 5. **SPBM** developers will learn from the initial progress made using **Q_i -based** model of MGFET.
 6. But the definitive MGFET model will be **SPBM**. Physics dictates this.
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CONCLUSIONS

- We have the tools, experience and infrastructure to base **compact MOSFET modeling** on the essential device physics: control of semiconductor conductivity by the **surface potential** ("Field-Effect").
 - The best V_{th} -based and Q_i -based models significantly advanced the MOSFET modeling field but their time has passed.
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