Unified Regional Charge-based Versus Surface-potential-based Compact Modeling Approaches


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ABSTRACT

This paper outlines the key features and advantages of the unified regional charge-based approach to MOSFET compact charge modeling in comparison with surface-potential-based approaches. Physical piecewise solutions are regionally derived from Pao–Sah equation, in which bulk charge is modeled by direct addition of accumulation and depletion charges based on the unified regional (source-end) surface potential. Drain-bias-dependent bulk and inversion charges are modeled with the unified regional charges in strong inversion using the non-pinned surface potential. Results have been compared with the iterative solutions and validated with numerical data. It has been extended to poly-accumulation/depletion/inversion effects and inversion charges are modeled with the unified regional charge expressions, from which output variables (e.g., terminal currents, charges) as a function of terminal voltages and device geometries, which requires “compacting” (i.e., integrating out) the spatial variables in the differential equations describing the behavior of device operations. This requirement, which is mandated by the computational speed requirement for large circuit-level matrix solutions, is trivial in numerical-based difference-equation solvers for the electrostatic potentials governed by the Poisson and current-continuity equations. However, in (quasi-static) CM, the aim is to obtain tractable analytical terminal charge expressions, from which transcapacitances can be obtained from the derivatives with respect to (w.r.t) terminal voltages, as well as terminal currents from spatial charge integration (with use of the effective mobility), from which transconductances are obtained from the derivatives w.r.t. terminal voltages.

In this paper, we attempt to explain the unified regional charged-based approach we are taking in our CM (Xsim) development in comparison with the surface-potential (φs)-based approaches, with an emphasis on charge modeling.

2 SURFACE-POTENTIAL SOLUTIONS

Rigorous MOSFET theory has been established by the well-known Pao–Sah equation [1,2] in the 60’s, which requires numerical solutions of the double integral for the terminal current. With the potential/charge balance and Poisson’s solution, the surface potential (φs) is related to the terminal gate voltage (Vgb) and channel voltage (Vch) by

\[ F \equiv V_{gb} - V_{ph} - \phi_s = \text{sgn}(\phi_s) \sqrt{f_\phi} \]  

(1a)

\[ f_\phi = v_{th} \left[ \exp \left( \frac{\phi_s}{v_{th}} \right) - 1 + \frac{\phi_s}{v_{th}} \right] + v_{th} \exp \left( \frac{V_{ch} + 25\phi_s}{v_{th}} \right) \]

(1b)

which has to be solved iteratively. In the above “original” Pao–Sah equation, the last term (\(\phi_s/v_{th}\))K where K \(\equiv \exp(V_{ch}/v_{th})\) is due to the contribution from the ionized donors (for nMOS). It is known [3] that either keeping or ignoring (K = 0) this term will result in non-convergence during iteration as \(V_{gb} \rightarrow V_{ph}\). This unphysical condition \(F^2 < 0\) as \(V_{ch} \rightarrow V_{ph}\), as pointed out by Sah [4] recently, is due to the approximation of neglecting the minority carriers in the quasi-neutrality boundary condition at large distance from the SiO2/Si interface. A remedy to this problem, which has been used in all iterative type of solutions in existing models, is to set K = 1 such that the derivative of f_\phi w.r.t. V_gb is always positive [3] and no negative \(F^2\) near \(V_{ph}\).

2.1 Implicit (Iterative) vs. Explicit (Analytical) Solutions

With the “modified” Pao–Sah equation (with \(K = 1\)), iterative \(\phi_s\) solutions can be obtained in all regions, which gives the “accurate” single-piece solutions usually used as a reference; and the computational speed is no longer a major problem in contemporary iterative algorithms [5,6]. Explicit (closed-form) analytical \(\phi_s\) solutions are all derived
with regional solutions in nature, some with absolute errors (w.r.t. iterative \( \phi_i \)) on the order of mV [7] and others of nV [8,9], the latter involved iterating analytical solutions on the “modified” Pao–Sah model [8]. These accurate \( \phi_i \) solutions contain the physics of MOSFET operations; however, such high accuracy is only mandated for compact charge/current models that are formulated with \( \phi_i \) as the intermediate variable to bridge the terminal voltages.

### 2.2 Piecewise vs. Unified Regional Solutions

Piecewise regional \( \phi_i \) solutions can be easily obtained by solving the regional Pao–Sah equation. E.g., in depletion, \( f_d \approx \phi_i \) and the solution of (1) has the simple form

\[
\phi_{sd} = \left( -\frac{\gamma}{2} + \sqrt{\frac{\gamma^2}{4} + V_{gd} - V_{fb}} \right)^2, \quad \left( V_{fb} < V_{gd} < V_f \right). \tag{2a}
\]

In accumulation, \( f_a \approx v_{th} \exp(-\phi/v_{th}) \) and the solution is given by the Lambert \( W \) function, \( L[w] \) [10]

\[
\phi_{se} = V_{gd} - V_{fb} + 2V_{th}L[w], \quad \left( V_{gd} < V_{fb} \right). \tag{2b}
\]

In strong inversion, with \( \phi_0 = \phi_{sd} = 2\phi_i \) approximating \( \phi_i \) and \( f_f \approx \phi_i + v_{th} \exp[(\phi_i - 2\phi_i - V_{fb})/v_{th}] \) in (1), solving for \( \phi_i \) one obtains [11]

\[
\phi_{se} = \phi_{sd} + V_{cb} + \Delta, \quad \left( V_{gd} > V_f \right) \tag{2c}
\]

\[
\Delta = v_{th} \ln \left[ \frac{1}{\gamma} \left( \frac{V_{gd} - V_{fb} - \phi_{sd}}{\gamma} - (\phi_{sd} + V_{cb}) \right) + 1 \right]. \tag{2d}
\]

The above piecewise solutions are plotted in Fig. 1 (crosses), which are valid only in the respective regions.

Although these piecewise solutions can be “glued” together to form a single-piece solution, it will inevitably introduce glitches at the transitions. The idea behind the “unified regional solution” is to use the following two smoothing functions

\[
V_{gh} = \theta_f \left[ x; \sigma_r \right] \equiv 0.5 \left( x + \sqrt{x^2 + 4\sigma_r} \right) \tag{3a}
\]

\[
V_{gh} = \theta_r \left[ x; \sigma_r \right] \equiv -0.5 \left( -x + \sqrt{x^2 + 4\sigma_r} \right) \tag{3b}
\]

(with \( x = V_{gd} - V_{fb} \)) to replace \( V_{gd} - V_{fb} \) in (2a) and (2b), respectively, thus, the two pieces of the unified regional solutions (Figs. 1, 2 dashed/dotted lines)

\[
\phi_{se} = \left( \frac{\gamma}{2} + \sqrt{\frac{\gamma^2}{4} + V_{gd}} \right)^2 \tag{4a}
\]

\[
\phi_{se} = V_{gd} + 2v_{th}L[w] \tag{4b}
\]

can be directly “added” \( (\phi_{oa} = \phi_{se} + \phi_{oa}, \text{ Fig. 2 } \ddagger) \), with asymptotic solutions approaching the piecewise solutions and transitions controlled by the two smoothing parameters. Similarly, \( \Delta \) in (2d) is smoothed out by \( \Delta = v_{th} \ln(b_{eff}) \), where

\[
b_{eff} = \frac{1}{v_{th}} \theta_f \left[ \frac{v_{th}}{\gamma} - (\phi_0 + V_{cb}); \sigma_{eff} \right] + 1 \tag{5a}
\]

\[
V_{ga} = \theta_f \left[ V_{ga} - V_{fb} - \phi_{oa}; \sigma_{ga} \right] \tag{5b}
\]

\[
\phi_{oa}^* = \phi_0 + V_{cb} + \frac{\phi_{se} - (\phi_0 + V_{cb})}{4v_{th}} \tag{5c}
\]

to obtain the unified regional “non-pinned” \( \phi_i \) solutions:

\[
\phi_{oa}(v_{th}) = \phi_0 + V_{cb} + \Delta \left( x_{\text{sat}} \right) \text{ (Fig. 1 solid line and Fig. 2 dash-double-dotted line)}, \quad \text{where } \Delta = v_{th} \ln(b_{eff})|_{v_{th} = V_{gb}} \text{ and } \Delta \left( x_{\text{sat}} \right) \text{ are evaluated at the source and drain ends, respectively.}
\]

Furthermore, a unified

\[
\phi_{oa} = \theta_f \left[ \phi_{se}; \sigma_r \right] \tag{6a}
\]

valid from depletion to strong inversion (Fig. 2 ’x’), is formulated with the smoothing function

\[
\theta_f \left[ x, x_{\text{sat}}; \sigma_r \right] \equiv x_{\text{sat}} - 0.5 \left( x_{\text{sat}} - x - \sigma_r \right) + \sqrt{\left( x_{\text{sat}} - x - \sigma_r \right)^2 + 4\sigma_r x_{\text{sat}}} \tag{6b}
\]

which can be directly added with \( \phi_{oa} \) to obtain the single-piece unified model \( (\phi_{eff} = \phi_{oa} + \phi_{oa}) \) for all regions (Fig. 2 solid line).

Although we have obtained a single-piece \( \phi_{eff} \) model for all regions, it will not be used in our charge model in the same way as other implicit/explicit \( \phi_i \)-based approaches. Rather, only the unified regional \( \phi_i \) solutions will be used in our unified regional charged-based modeling, and the distinctive advantages of the approach will be made clearer in the ensuing sections.

### 2.3 “Stitched” vs. “Glued” Explicit Solutions

One unique property of the unified regional model is that, although each regional piece starts to deviate from the physical solution beyond its validity region, the (combined) unified single-piece model gives the physical solution, which can be “tuned” by the smoothing parameter(s) to satisfy the physical solution as well as smoothness, e.g., tuning \( \sigma_r \) to obtain \( \phi_i = 0 \) exactly at \( V_{ga} = V_{fb} \) (Fig. 4 inset) and tuning \( \sigma_r \) for smoothness in the second-order derivative of \( \phi_i \) around \( V_{fb} \) (see more in Sec. 3.3 and [12] for parameter tuning). In this sense, the \( \phi_{eff} \) (also \( \phi_{oa} \)) solution across \( V_{fb} \) is “stitched” together from two pieces, rather than being “solved” exactly by implicit/explicit iterations and, hence, it is seamless with \( C_s \) continuity (Fig. 2 inset) without any “if” conditions in implementation \( (V_{gb} \text{ can be arbitrarily close to } V_{fb}) \). Smoothing parameter tuning does not require any data and their values are fixed for all bias and physical parameter variations.

In comparison with the explicit \( \phi_i \) solution [9], a small ripple in the second derivative of \( \phi_i \) can be seen, as shown in Fig. 3, due to the solution being connected (or “glued”) together by three pieces, although the function \( \phi_i \) itself is continuous with nV error w.r.t. iterative \( \phi_i \) solutions.
2.4 “Pinned” vs. “Non-pinned” Surface Potentials

The “non-pinned” \( \phi \) model (\( \phi_{sp} = \phi_{d0} + V_{cb} + \Delta \)) is an extension to the “pinned” model, which is the conventional threshold-voltage (\( V \))-based model (i.e., \( V_{sp} = V \) when \( \phi_{sp} = 2\phi_{d} + V_{sb} \), with \( \Delta = 0 \)). The advantage is that while building in the physics contained in the \( \phi \) solutions, the concept as well as the model of \( V \) is still retained. In this sense, “non-pinned” \( \phi \) model combines the advantages of both \( V \)-based and \( \phi \)-based models. Not only the familiar (\( V \))-based formulations can still be used, but it is also easier to include short-channel effects (SCEs), such as DIIBL, CLM, velocity saturation/overshoot [13] from quasi-2D solutions [14], as well as bias-dependent series resistance in CLM, velocity saturation/overshoot [13] from quasi-2D sense, “non-pinned” \( \phi \) model employs the concept of lateral-field gradient [15,9] in the building in the physics contained in the \( \phi \) solutions, the concept as well as the model of \( V \) is still retained. As a matter of fact, \( \phi \)-based models employ the concept of lateral-field gradient [15,9] in the \( \phi \) solution to account for SCEs, which has limitations to model extremely-scaled devices (with large \( V \); roll-off, e.g., Fig. 9 in [16]). Moreover, almost all existing \( \phi \)-based models (except for [5]) use “effective drain–source voltage” (with mathematical smoothing) to treat saturation effect, which would undermine the often claimed “high physical content” from the \( \phi \) solutions since it is highly dependent on how the velocity-saturation region is being modeled as well as the smoothing parameter (which is often geometry dependent). In particular, a claim on inclusion of velocity-overshoot effect will not be true unless the formulation is derived from energy-balance transport equations [13,17].

3 TERMINAL CHARGE MODELS

Even though (iterative, explicit, unified regional) \( \phi \) solutions are readily available, to obtain total terminal charges, channel-position-dependent charge densities have to be integrated out. One of the difficulties is the non-integrable term \( \exp[-\phi(y)/\bar{\gamma}] \) [3] in the channel space charge \( Q_{ch}(y) \) [sum of bulk (\( Q_{b} \)) and inversion (\( Q_{i} \)) charges]

\[
Q_{ch} = Q_{b} + Q_{i} = -\operatorname{sgn}(\phi_{d}) \bar{C}_a \bar{\gamma} \sqrt{\bar{g}} \tag{7a}
\]

from the right-hand side of (1), which is important near and below flat-band; or from charge neutrality and the left-hand side of (1) [sum of gate (\( Q_{g} \)) and fixed oxide (\( Q_{ox} \)) charges]

\[
Q_{ch} = -\{Q_{g} + Q_{ox}\} = -\bar{C}_a \left( V_{gb} - V_{jb} - \phi_{d} \right). \tag{7b}
\]

3.1 Implicit/Explicit Surface-potential-based Model

\( \phi \)-based (either iterative or explicit) models\(^1\) express integrated terminal charges as a function of \( \phi \) [18]. Choices of the independent charges can be \{\( Q_{b}, Q_{i} \)} [5].

\[\{Q_{g}, Q_{ox}\} [9,19], \text{or} \{Q_{g}, Q_{b}\} [20]\]

while calculating the other terminal charge from charge neutrality (\( Q_{d} \) is normally from Ward–Dutton partition [21] and \( Q_{d} = Q_{s} - Q_{b} \)). Some models solve source-end \( \phi(0) \) only (together with effective drain voltage) while others solve both source-end and drain-end \( \phi(L) \), with midpoint or symmetric bulk-change linearization. High accuracy in \( \phi \) solutions is generally required since source–drain surface potential difference is very small and the current is an exponential function of \( \phi \).

3.2 (Inversion) Charge-based Model

(Inversion) charge-based models\(^1\) normally start with the charge-sheet [22] and depletion approximations for the bulk charge together with inversion-charge linearization, which results in an implicit “charge-control” model for the inversion charge, and the drain current is a quadratic and linear function of the drain/source-end charge densities. This approach uses \( Q_{d} \) as the intermediate variable and does not require accurate \( \phi \) solutions. Accumulation region needs to be modeled separately.

3.3 Unified Regional Charge-based Model with Non-pinned Surface Potential

A unique feature of our unified regional charge-based approach is in the bulk-charge modeling in depletion and accumulation regions (\( V_{gs} \ll V \)), which is based on the unified regional surface potentials (\( \phi_{gb} = \phi_{acc} + \phi_{sub} \)) rather than dependent on the source/drain-end surface potential difference (\( \phi(L) - \phi(0) \)) and, hence, no need for high accuracy in \( \phi \) solutions. By introducing a new “forward” smoothing function \( V_{gba} = \bar{Q}_{b} \{ V_{gb} - V_{jb}; \sigma_{b} \} \) with the same parameter (\( \sigma_{b} \)) as in \( V_{gb} \) (3b), it can be shown that

\[
\bar{Q}_{gb} = -\bar{C}_a \left( V_{gb} - V_{jb} - \phi_{d} \right), \tag{8a}
\]

\[
\bar{Q}_{b,acc} = -\bar{C}_a \left( V_{gb} - \phi_{acc} \right), \tag{8b}
\]

where we have used

\[
-\bar{C}_a (V_{gb} - \phi_{acc}) = -\bar{C}_a \sqrt{\phi_{sub}} \equiv \bar{Q}_{b,sub} \tag{8c}
\]

based on (7) using the same smoothing parameter (\( \sigma_{b} \)).

When \( \phi_{sub} \) in (8b) is replaced by \( \phi_{d0} \) in (6a) evaluated at \( V_{cb} = V_{sb} \), we obtain a single-piece bulk charge for zero \( V_{ds} \) (\( Q_{bs} \)) from accumulation to strong inversion (Fig. 4 and the corresponding \( C_{bs} \) in Fig. 5):

\(^1\) See [18] in this volume for a comprehensive review on surface-potential and (inversion) charge-based models.

\(^2\) Ignoring \( Q_{s} \) and \( Q_{ox} \) is justified in regional solutions but may not be true in exact implicit/explicit Pao–Sah solutions near \( V_{fb} \).
\[ Q_{sb} = Q_{d,acc} + Q_{d,de} \]  
\[ Q_{d,de} = -C_{ox} \left( V_{gsa} - V_{th} + \gamma \sqrt{\phi_{d,s}} \right). \]  
\[ (9a) \]
\[ (9b) \]

Following the same approach as conventional charge-sheet approximation in deriving terminal charges, with the integration boundaries changed to the non-pinned surface potentials at the source \( \phi_s(0) = 2\phi_p + V_{fb} + \Delta_s \) and drain \( \phi_d(L) = 2\phi_p + V_{fb} + \Delta_s \) terminal charges can be derived, which take the similar forms [24] as for pinned-\( \phi \) model. This gives an added advantage for the consistency with textbook equations as well as selectable accuracy using the same parameter set. \( V_{fb} = V_{th} - V_{in} \) is used in the unified charge model; thus, our charge model is essentially source-referenced with drain-end being modeled as a difference \( \Delta_{d,de} = \Delta_{eff,d} - \Delta_{eff,s} \) where \( \Delta_{eff,d} = \phi_{eff} - (\phi_d + V_{fb}) \) due to non-zero \( V_{fb} \). \( Q_d = -(Q_s + Q_c + Q_{sub}) \) is obtained from charge neutrality. The \( V_{d,s} \)-dependent component of \( Q_s \) (“\( \Delta_{eff} \)” [24]) is added to \( Q_{do} \) (9a), which approaches zero in the depletion/accumulation regions, thus, \( Q_s \) is independent of the well (Fig. 4 and 5 (dash-dotted lines)).

### 4 EXTENSION TO NON-INTRINSIC NON-BULK EFFECTS

#### 4.1 Poly Accumulation/Depletion/Inversion

When the surface potential on the poly-gate side (\( \phi_p \)) is considered, another Pao–Sah equation can be derived

\[ V_{gb} - V_{pb} - \phi_p = \text{sgn}(\phi_p)\gamma_p \sqrt{f_{pb}} \]  
\[ (10) \]

in which \( f_{pb} \) is similar to (1b) with \( \phi_p \) replaced by \( \phi_b, \phi_p \) by \( \phi_{p,b,p} \), and \( V_{pb} = 0 \). Eq. (10) is coupled to (1) to be solved with two iterations. By considering only the accumulation charges in the gate and channel and equating the right-hand side of the two Pao–Sah equations,

\[ \gamma \text{sgn}(\phi_p) \sqrt{v_{th} \left( e^{\gamma_p \phi_p} - 1 \right)} = \gamma_p \text{sgn}(\phi_p) \sqrt{v_{th} \left( e^{\phi_p} - 1 \right)}, \]

an explicit \( \phi_{p,acc} \) in accumulation can be derived [25]

\[ \phi_p = \phi_{p,acc} = -v_{th} \ln \left[ \frac{\gamma_p^2 \exp(-\phi_p/v_{th}) - 1 + \gamma_p^2 \exp(-\phi_p/v_{th})}{\gamma_p^2 \exp(-\phi_p/v_{th}) - 1}\right]. \]  
\[ (11) \]

Similarly, unified regional depletion (\( \phi_{p,sub} \)) and strong-inversion (\( \phi_{p,inv} \)) surface potentials can be obtained with \( V_{gb} - V_{pb} - \phi_{eff} \) as the argument in the corresponding smoothing functions (3) and (5b), from which a single-piece unified \( \phi_{eff} \) can be constructed (Fig. 7). Two smoothing parameters (\( \rho_p, \rho_s \)) are introduced to tune \( \phi_p = 0 \) at \( V_{pb} \) [12]. \( \phi_{eff} \) is then modified by changing the argument in the smoothing functions to \( V_{gb} - V_{pb} - \phi_{eff} \) to arrive at the final explicitly coupled \( \phi_{eff} \) and \( \phi_{eff} \) solutions. Thus, Poly-Accumulation/Depletion/Inversion Effects (PAE/PDE/PIE) are all included in our unified charge model (from regional Pao–Sah solutions) for all terminal bias dependencies [25].

#### 4.2 Coupled Quantum-Mechanical Effect

Quantum-Mechanical Effect (QME) is introduced into our regional Pao–Sah \( \phi_p \) and \( \phi_s \) solutions based on the van Dorst QM model [26] via the increase in the bandgap \( \Delta E_g \), which is a function of \( \phi \) that modifies the Pao–Sah Eqs. (1) and (10) by the addition of the factor \( qm^2 \equiv \exp(\pm \Delta E_g/qm) \)

\[ f_{pb}^{qm} = v_{th} \left( \frac{\phi_p}{v_{th}} \exp(-\phi_p/v_{th}) - 1 + \frac{\phi_p}{v_{th}} \right) + v_{th} \exp\left( -\frac{V_{th} + 2\phi_p}{v_{th}} \right) \]

and a similar one for \( f_{pb}^{qm} \). In principle, \( \phi_p \) and \( \phi_s \) as well as \( \Delta E_g^{qm}(\phi) \) are all coupled. Through regional (accumulation and inversion) solutions, we have obtained decoupled explicit \( \phi_{eff}^{qm} \) and \( \phi_{eff}^{qm} \) solutions for modeling QME and PAE/PDE/PIE separately and combined, as validated by comparison with Medici device data (Fig. 8).

#### 4.3 Heterostructure FETs (Strained-Si)

Another advantage of the unified regional approach is its easy extension to modeling heterostructure FETs such as strained-silicon (s-Si) MOSFETs. We have developed a model [27] extending our bulk-Si charge model to s-Si, in which the well-known “plateau” in \( C_{bg} \) due to hole accumulation at the s-Si/SiGe interface is modeled by applying the same accumulation/depletion regional model to this interface (Fig. 9). The complete model is scalable with SiGe mole fraction, s-Si thickness and doping, due to the physically derived flat-band voltages at the s-Si/SiO\(_2\) (\( V_{fb} \)) and s-Si/SiGe (\( V_{fg} \)) interfaces.

### 5 SUMMARY AND CONCLUSIONS

We have demonstrated that through careful selection of interpolation/smoothing functions, the unified regional approach to compact charge modeling has unique advantages, which combines the features of surface-potential, threshold-voltage, and charge-based models. Physics-based regional solutions are justified in the regionally derived equations, which has an added advantage of familiar “textbook” equations as well as selectable accuracy between simple model for long/wide and full model for short/narrow devices using one parameter set.

The final judgment on a compact model is still on how well (how accurate, efficient, easy) it models real devices.
of varying geometries for a given technology. It will not be surprising that the deviations of the modeled results among various approaches (surface-potential, charge-based, or otherwise) would be less than the fluctuations from real device data on the same wafer. Our unified regional approach (combining the features from $V_t/\phi_s/Q_s$-based approaches) is an attempt to build the core model for achieving the ultimate goal with potential for easy extension to model non-idealities and future generation device structures.

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REFERENCES

[20] R. Rios, private communications; also [18].

Figure 1: Piecewise (crosses) and unified regional (lines) $\phi_i$ solutions, compared with iterative solution (circle).

Figure 2: Unified regional $\phi_i$ solutions and the combined (“stitched”) solutions ($\phi_{\text{sub}}$ (accumulation/depletion) and $\phi_{\text{eff}}$ (all region) as well as its 1st/2nd-order derivatives (inset).

Figure 3: Explicit analytical $\phi_i$ solution based on [9] with 3 regional pieces “glued” into one. A small ripple in the 2nd-order derivative is observable (inset, dotted line) when the voltage step size is very small.

[27] K. Chandrasekaran et al., submitted for publication.
Gate−Source Voltage, $V_{gs}$ (V)

-2 -1 0 1 2

Figure 4: Unified regional bulk charge in accumulation ($Q_{b,acc}$) and depletion/inversion ($Q_{b,ds}$) and the $V_{ds}$-dependent component ($-C_{ox}Db,\Delta$). The inset shows tuning for charge neutrality at flat-band.

Gate−Bulk Voltage, $V_{gb}$ (V)

-2 -1 0 1 2

Figure 6: Channel, drain, source capacitances from the derivatives of $Q_b$ in Fig. 4 w.r.t. $V_{gb}$. The inset shows smoothness of $C_{bg}$.

Gate−Bulk Voltage, $V_{gb}$ (V)

-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0

Figure 9: Unified regional charge model applied to strained-Si to model the $C_{bg}$ “plateau” due to hole accumulation at the s-Si/SiGe interface.

Gate−Source Voltage, $V_{gs}$ (V)

-2 -1 0 1 2

Figure 5: The corresponding derivatives of $Q_b$ in Fig. 4 w.r.t. $V_{gb}$. The inset shows tuning for charge neutrality at flat-band.

Gate−Bulk Voltage, $V_{gb}$ (V)

-2 -1 0 1 2

Figure 8: Gate capacitance from the explicit charge model with coupled QME and PAE/PDE, compared with Medici data (symbols) using the same $\kappa_{qm}$ values.

Gate−Bulk Voltage, $V_{gb}$ (V)

-2 -1 0 1 2

Figure 7: Unified regional and explicit poly-gate $\phi$ solutions using explicit $\phi_{seff}$ (lines) and iterative $\phi$ (cross), compared with numerical data (i.e., iterative $\phi$ and $\phi_p$) probed from Medici device.