USIM Design Considerations

D. Averill Bell
Kumud Singhal
Hermann K. Gummel

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Outline

- Goals
- Inversion Charge
- Drain Current
- “Threshold”
- Symmetry
- Conclusion

Model Design Goals

- Tradeoff between accuracy and compactness
- Accurate circuit simulations [11]
    - Well approximated, quantitatively and qualitatively
    - Meets analog requirements
    - Understandable; trustworthy
- Efficient and compact implementation
    - Easy to extract; small set of parameters
    - Go as far as possible with clean physics, then use well behaved empirical relations
- Fast, robust: simulates quickly and converges well

USIM Model Overview

Terminology: NMOS polarity; lower case voltages normalized by thermal voltage kT/q and charge densities normalized by $-C_{ox}kT/q$.

- Inversion charge density q_m: Function of v_{gb} and v_{ch}, the local channel voltage.
- Saturation voltage v_{sat}: Function of v_{gb} only, not v_{ch}. v_{sat} is the v_{ch} at $q_m=1$.
- Local threshold voltage v_{th}: Function of v_{ch} and thus channel position. Secondary parameter.
- Efficient, robust q_m calculation. Easier to calculate q_m directly than from ψ_s. Focusing on q_m near 1 bridges the regimes below and above threshold.

Inversion Charge

For constant substrate doping, the 1-D Poisson equation can be integrated to obtain the total silicon charge

$$q_{tot} = \pm\gamma^2 \sqrt{\left(\psi_s + e^{-\psi_s} - 1\right) - e^{-2\phi_F - v_{ch}}\left(\psi_s + e^{\psi_s} - 1\right)} \qquad (1)$$

where

- $\gamma^2 = \frac{2q\varepsilon_{si}N_a}{C_{ox}}\frac{q}{C_{ox}kT}$
- the hole Fermi potential $\phi_F \approx \ln(N_a/n_i)$
- ψ_s is relative to deep bulk value
- sqrt sign is sign of ψ_s

This numerical detail is needed to avoid the square root of a negative number when calculating the bulk charge in depletion for $\psi_s \approx 0$.

Inversion charge (2)

When q_m is significant and using the depletion approximation, (1) simplifies to

$$q_{tot} = q_m + q_b = \sqrt{\gamma^2 \psi_s + \gamma^2 e^{\psi_s - 2\phi_F - v_{ch}}} \qquad (2)$$

As $q_m \rightarrow 0$, $\gamma^2 \psi_s = q_b^2$. The charge sheet approximation is to assume this remains true when $q_m > 0$.

For a general substrate doping,

$$q_{tot} = \sqrt{q_b^2 + \gamma_z^2 e^{\psi_s - \phi_F - v_{ch}}} = \sqrt{q_b^2 + \gamma_z^2 e^{\psi_{sr} - v_{ch}}} \qquad (3)$$

where ψ_{sr} is relative to the hole quasi Fermi potential and γ_z uses n_i instead of N_a as a reference:

$$\gamma_z^2 = \frac{2q\varepsilon_{si} n_i}{C_{ox}} \frac{q}{C_{ox} kT} \qquad (4)$$

Inversion charge (3)

Solving (3) for ψ_{sr}

$$\psi_{sr} = v_{ch} + \ln(q_m) + \ln(q_m + 2q_b) - \ln(\gamma_z^2) \qquad (5)$$

From charge balance,

$$\psi_{sr} = v_{gb} - \phi_{ms} - q_m - q_b \qquad (6)$$

q_b is function of $(v_{gb}\text{-}q_m)$ and ϕ_{ms} is gate-sub W.F. Eliminating ψ_{sr}

$$(q_m - 1) + \ln(q_m) = \left[v_{gb} - v_{fb} - 1 - q_b - \ln(2q_b + q_m) + \ln(\gamma^2) - 2\phi_F\right] - v_{ch} \qquad (7)$$

Setting $q_m=1$, we define

$$v_{sat} = v_{gb} - \phi_{ms} - 1 - q_b - \ln(2q_b + 1) + \ln(\gamma_z^2) \qquad (8)$$

In the case of constant doping

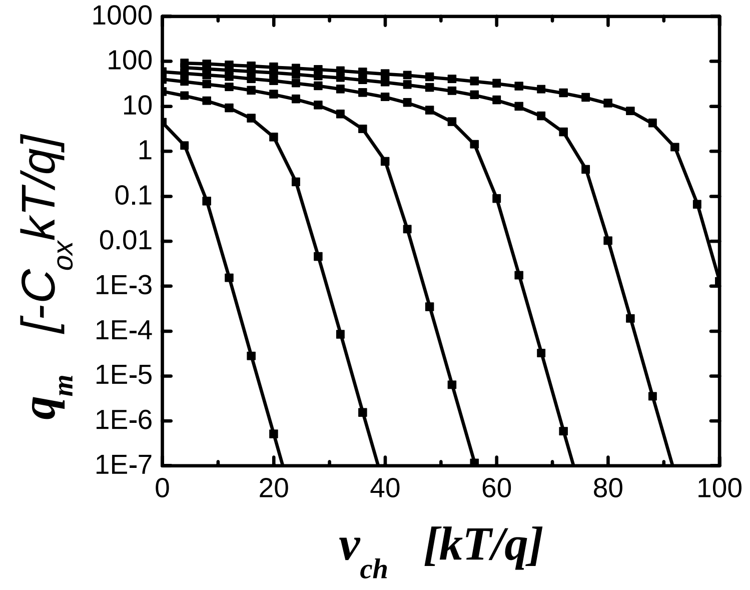
$$v_{sat} = v_{gb} - v_{fb} - 1 - q_b - \ln(2q_b + 1) + \ln(\gamma^2) - 2\phi_F \qquad (9)$$

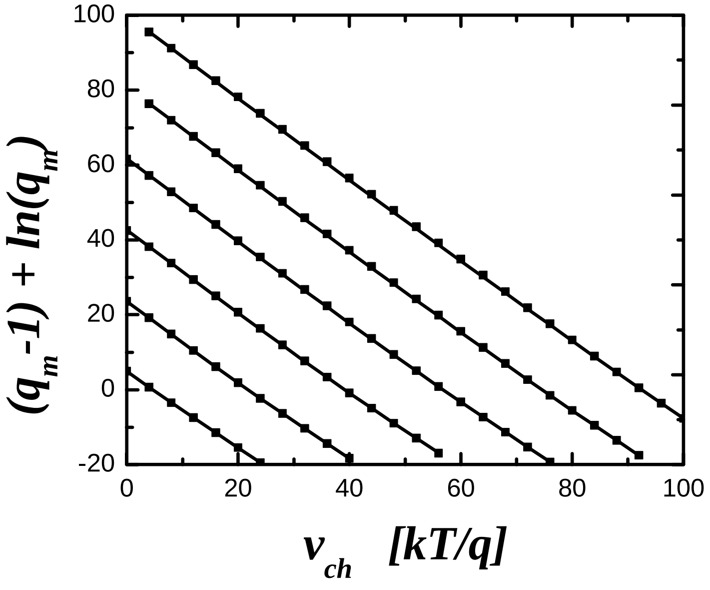
Inversion Charge (4)

Eq. (7) and (8) lead to the *inversion charge relation*

$$\boxed{h_x(q_m - 1) + \ln(q_m) = v_{sat} - v_{ch}} \qquad (10)$$

h_x captures small delta between v_{sat} and bracketed portion of (7). For GIBL reduced sub-slope at short L, multiply $\ln(q_m)$ by t_e. Similar expressions in [1-3]. In figures: points=(7); curves=(10)





Drain Current

The channel current is given by the horizontal gradient of v_{ch}

$$i = \mu_{eff}\, q_m \frac{dv_{ch}}{dy} = -\mu_{eff}\, h_x \frac{d}{dy}\left(q_m + \frac{t_e}{h_x}\right)^2 \qquad (11)$$

including t_e. Continuity ⇒ i constant. Assuming effective mobility μ_{eff} is independent of y, easily integrate (11) to obtain the channel current relation based on q_m at the end points:

$$I = \beta\left(h_x \frac{q_{ms}^2 - q_{md}^2}{2} + t_e\left(q_{ms} - q_{md}\right)\right) \qquad (12)$$

where

$$\beta = \mu_{eff}\, C_{ox}\left(\frac{kT}{q}\right)^2 \frac{W}{L} \qquad (13)$$

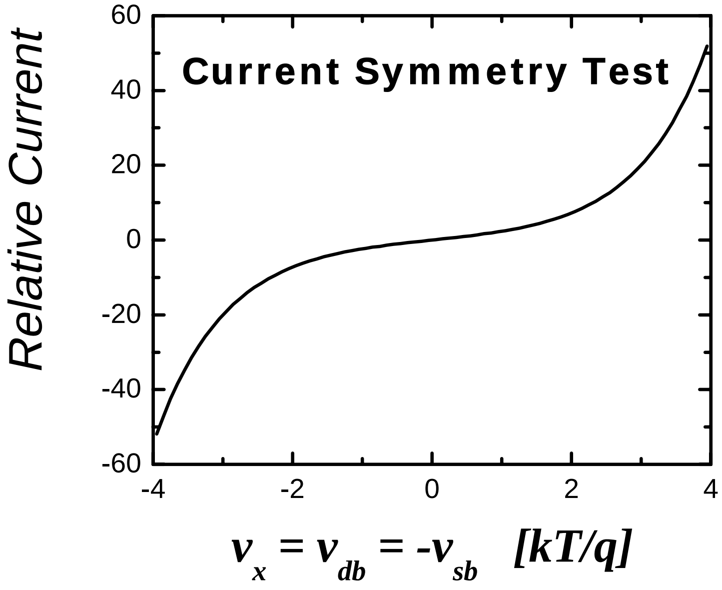
This relation covers all regions of operation and is consistent with published work [2,6,7].

Subthreshold Limit

The channel current relation (12) has various simple limits. In subthreshold, q_{ms} and q_{md} are much smaller than unity so:

$$I = \beta t_e \left(q_{ms} - q_{md} \right) \tag{14}$$

For $q_m << 1$, the inversion charge relation (10) simplifies to:



$$t_e \ln\left(q_{ms}\right) = v_{sat} - v_{sb} + h_x \tag{15}$$

and similarly for q_{md}. Thus:

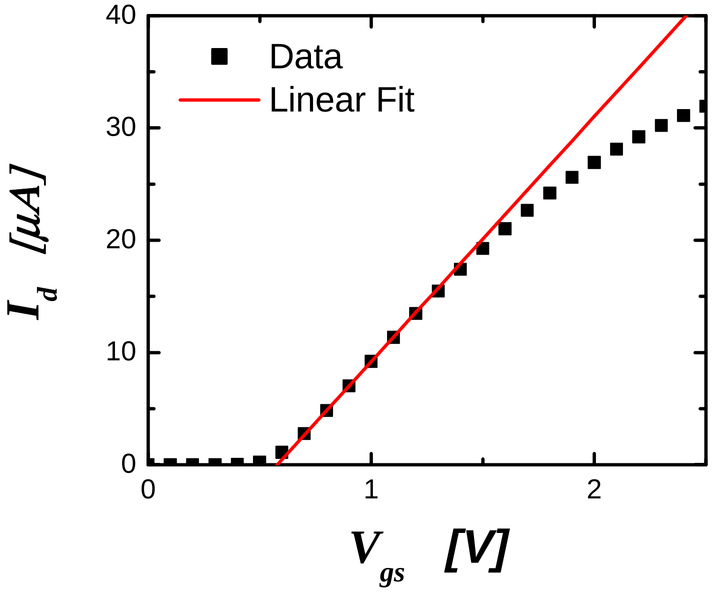
$$I = \beta t_e e^{(v_{sat} + h_x)/t_e} \left(e^{-v_{sb}/t_e} - e^{-v_{db}/t_e} \right) \tag{16}$$

Threshold Condition

In USIM, the internal threshold condition is defined to occur at $q_m=1$, which corresponds to an unnormalized inversion charge density of $-C_{ox}kT/q$.

At threshold condition, $v_{ch} = v_{sat}$ and we define $v_{th} = v_{gb}-v_{ch}$. According to this definition, v_{th} depends on channel position for $v_{ds} \neq 0$.

Note these definitions refer to unity inversion charge. Some external threshold definitions, such as peak-gm, focus on currents above threshold.



Surface Potential at Threshold

Historically, ψ_s at threshold is approximated as $2\phi_F + v_{ch}$. Define $\Delta\psi_s$ by

$$\psi_s = 2\phi_F + v_{ch} + \Delta\psi_s \qquad (17)$$

For USIM with constant doping, starting from (2) and setting $q_m = 1$ gives

$$\begin{aligned} \Delta\psi_s &= \ln\left(2\gamma\sqrt{\psi_s} + 1\right) - \ln(\gamma^2) \\ &\approx \ln\left(2\gamma\sqrt{2\phi_F + v_{ch}} + 1\right) - \ln(\gamma^2) \end{aligned} \qquad (18)$$

For $v_{ch} = 0$, (18) is on the order of a few kT/q.

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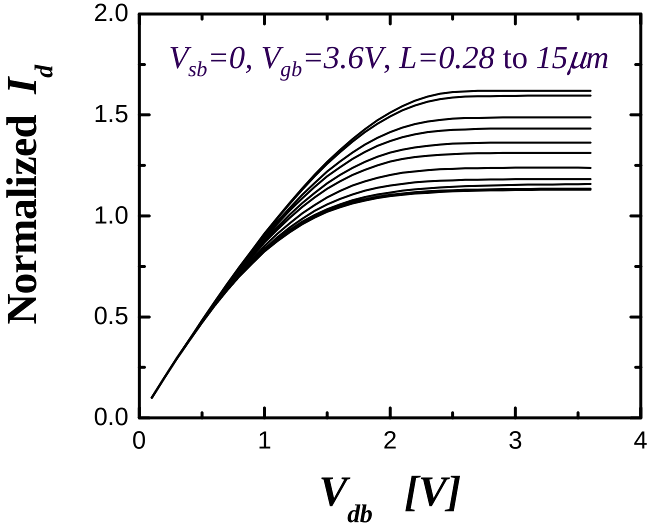
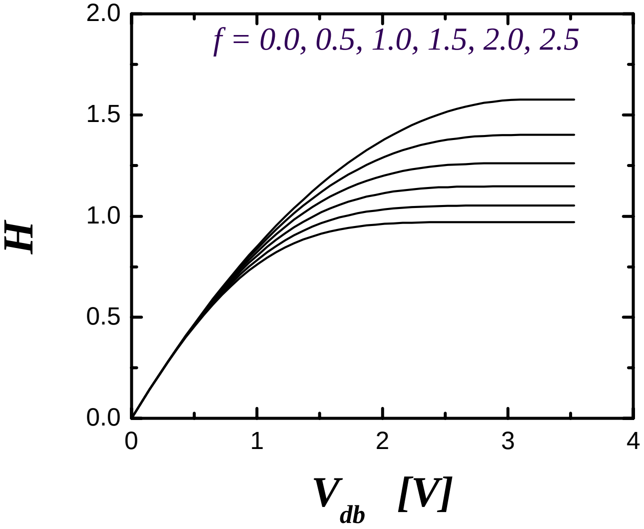
Symmetry

- Symmetry is a fundamental physical property and, for smoothness, accuracy and credibility, should be built into the equations, not fixed after the fact.
- It arises naturally when starting from basic physical equations.
- Empirical equations also should be written symmetrically. Preferably they should be simple yet flexible enough to fit data.

Symmetry (2)

Consider saturation. Physics is complex, but note similar *IV*. Inversion charge relation (10) still applies except at S/D ends. Need symmetrical, empirical function of q_{ms} and q_{md}.


Measured Data


Function *H*

Found quadratic terms in channel current relation (12) could be replaced by:

$$H = \frac{2}{f+4} \frac{q_{ms}^{f+4} - q_{md}^{f+4}}{q_{ms}^{f+2} + q_{md}^{f+2}} \qquad (19)$$

where f is bias dependent.

USIM Design Summary

- Balance between accuracy and efficiency
- Clean physics where possible
- Well behaved empirical relations

- Complete S/D symmetry, handles general q_b and all regions of operation seamlessly.
- Simple, implicit relation for q_m as function of v_{gb} and v_{ch} to avoid need for calculating ψ_s.
- Model concept: threshold condition at $q_m=1$
- Emphasis on sat. voltage v_{sat} rather than v_{th}.

References

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