Presentation/Publication Information:
Talk to be given by Bryan Biegel at the American Physical Society (APS) Centennial Meeting, March 23, 1999, Atlanta, GA. This material will also be published on the Web. A copy of the presentation is attached.

Acknowledgments:
This work was supported under NASA contract NAS2-14303.

Abstract:
We show that quantum effects are likely to significantly degrade the performance of MOSFETs as these devices are scaled below 100 nm channel length and 2 nm oxide thickness over the next decade. A general and computationally efficient electronic device model including quantum effects would allow us to monitor and mitigate these effects. Full quantum models are too expensive in multi-dimensions. Using a general but efficient PDE solver called PROPHET, we implemented the density-gradient (DG) quantum correction to the industry-dominant classical drift-diffusion (DD) model. The DG model efficiently includes quantum carrier profile smoothing and tunneling in multi-dimensions and for any electronic device structure. We show that the DG model reduces DD model error from as much as 50% down to a few percent in comparison to thin-oxide MOS capacitance measurements. We also show the first DG simulations of gate oxide tunneling and transverse current flow in ultra-scaled MOSFETs. The advantages of rapid model implementation using the PDE solver approach will be demonstrated, as well as the applicability of the DG model to any electronic device structure.
Multi-Dimensional Quantum Tunneling and Transport Using the Density-Gradient Model

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Outline

• Motivation
• Density-Gradient Model
• Quantum Confinement
• Quantum Tunneling
• Conclusions

Tunneling and Transport in MOSFETs

Density-Gradient Model

Density-Gradient Model (quantum-corrected drift-diffusion):

\[ \frac{\partial n}{\partial t} = \nabla \cdot \left[ D_n \nabla n + n \mu_n \nabla (u + u_{qn}) \right] \]

\[ u_{qn} = 2b_n \left( \frac{\nabla^2 n}{\sqrt{n}} \right) \]

\[ b_n = -\frac{\hbar^2}{12m_n^* q} \]

\[ \frac{\partial p}{\partial t} = \nabla \cdot \left[ D_p \nabla p + p \mu_p \nabla (u + u_{qp}) \right] \]

\[ u_{qp} = -2b_p \left( \frac{\nabla^2 p}{\sqrt{p}} \right) \]

\[ b_p = \frac{\hbar^2}{12m_p^* q} \]

Effect of quantum potential:

MOSFET Structure

Drift-Diffusion Model

Density-Gradient Model

Need 2-D/3-D electronic transport model with quantum effects, but...

- Quantum computations still too slow
- Drift-diffusion (classical) model is industry work-horse
**Quantum Confinement - Carrier Profiles**

**Channel Inversion (V_G=1V)**

Conclusions:
- Quantum confinement significantly changes inversion charge profile.
- Densities decrease exponentially into oxide.

**Channel Accum. (V_G=1.5V)**

**MOS Gate Capacitance**

**1-D MOS Capacitor Model**

Conclusions:
- DG model greatly improves accuracy.
- Classical model diverges rapidly below T ox = 4nm.

**30 nm MOSFET - Drain Characteristic**

**2-D MOSFET Model**

Conclusions:
- MOSFET still works at 30nm channel length.
- Quantum effects reduce current by up to 60%.
- Current decrease due to reduced channel charge.

**30 nm MOSFET - Gate Oxide Tunneling**

**2-D MOSFET Model**

Conclusions:
- Gate leakage decreases with increasing drain bias.
- Gate leakage greater than OFF drain current.
- Tunnel current highest near source, drain.
Conclusions

- Density-Gradient transport model:
  - Similar to industry standard model (DD)
  - Moderate additional computation
  - Quantum confinement, tunneling

- Simulated quantum effects
  - MOS Capacitor: dramatic improvement in accuracy
  - Small MOSFET: $I_D$ decrease = $Q_{channel}$ decrease
  - First 2-D DG tunneling: S/D tunneling "hot-spots"

Future DG Tunneling Model

Simple Density-Gradient model assumes diffusive tunneling!
Under development: "two-fluid", lossless, inertial tunneling model

Why?

How? PROPHET: Script-based PDE solver (Lucent Technologies)