Simulation of Ultra-Small MOSFETs Using a 2-D Quantum-Corrected Drift-Diffusion Model

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Outline
• Motivation
• Density-Gradient Model
• Bipolar Devices (1-D and 2-D)
• MOS Devices (1-D and 2-D)
• Device Modeling with PROPHET
• Conclusions
Quantum Effects in Electronics

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

Density-Gradient Model

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

\[
\begin{align*}
\frac{\partial n}{\partial t} &= \nabla \cdot \left[ D_n \nabla n - n \mu_n \nabla (u + u_{qn}) \right] \\
\frac{\partial p}{\partial t} &= \nabla \cdot \left[ D_p \nabla p + p \mu_p \nabla (u + u_{qp}) \right] \\
\end{align*}
\]

Effect of quantum potential:

\[
\begin{align*}
\mu_n &= 2 b_n \left( \frac{\nabla^2 \sqrt{n}}{\sqrt{n}} \right) \\
\mu_p &= -2 b_p \left( \frac{\nabla^2 \sqrt{p}}{\sqrt{p}} \right) \\
b_n &= \frac{-\hbar^2}{12 m_n^* q} \\
b_p &= \frac{\hbar^2}{12 m_p^* q} \\
\end{align*}
\]
**P-N Diode (1-D)**

Conclusions:
- Lower mass results in more quantum smoothing
- Terminal characteristics of diode unaffected by DG

**Bipolar Junction Transistor (2-D)**

DG base current 20% *smaller* ⇒ DG current gain is *higher*
Quantum effects *improve* operation?
MOS Capacitor (1-D)

1-D MOS Capacitor Model

Conclusions:
- DG model greatly improves accuracy
- Classical model diverges rapidly below $T_{OX} = 40\text{Å}$

MOS Capacitor Details

- Gate Capacitance vs. Gate Voltage
  - Classical
  - DG
  - Exp. (HP)

- Oxide Thicknesses: 44, 52.5, 79.5, 21, 25.5, 31 Å

- Equation: $C \sim \varepsilon A/T_{OX}$
  - $A = (100 \mu\text{m})^2$
Conclusions:

- MOSFET still works at 30 nm!
- Quantum effects reduce current up to 60%
- Current decrease due to reduced channel charge

- Quantum effects less severe (35Å oxide)
- Computed current 15X measured current!
- Better mobility model needed: $\mu(L, II, CC, N, S, E)$
Ionized Impurity Scattering

Mobility model:
\[ \mu_I = \mu_{\text{min}} + \frac{\mu_0 - \mu_{\text{min}}}{1 + \left( \frac{N}{N_{\text{ref}}} \right)^\alpha} \]

DG model works with position-dependent mobility

Transport Model Development Approach

Standard, single-model approach:
- Formulation to results-analysis is LONG
- Code structure restricts future enhancements
- Single-model code eventually discarded

PDE Solver Approach:

Derive physical model

Convert to numerical model

Program

Debug

Enhance numerical methods, gridding, efficiency, graphics

Run simulations

Analyze results

Ideal Device Simulator

I-V

C-V

V(x,y)

V(x,y)

V(x,y)
**PROPHET PDE Solver**

Features of PROPHET:
- Script-driven: models, parameters, simulations, output
- Operator set: differential, arithmetic, process/device-specific
- Database storage/access of all models, user input
- Gridding: finite difference, finite element; 1-D, 2-D, 3-D
- Linear solver: PETSc (Lucent: internal solver)
- Boundary conditions: Dirichlet, Neumann, anywhere, anytime
- Steady-state and transient capability
- Xgraph output
- New operators usually painless to create

**PROPHET Development Examples**

- Drift-Diffusion version of DG model: 2 months
  - Solution variables: $\psi, n, p, \psi_q, \psi_p$
- Quasi-Fermi version of DG model: 1 month
  - Solution variables: $\psi, n, p, \sqrt{n}, \sqrt{p}$
- Ionized impurity scattering: 1 hour

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MOSFET Structure

Drift-Diffusion Model

Density-Gradient Model
Conclusions

- Described the Density-Gradient transport model
- Simulated quantum effects in electronic devices
  - P-N diode (1-D): no quantum effect (Esaki tunneling next)
  - BJT (2-D): higher current gain (beta analysis)
  - MOS capacitors (1-D): Quantum effects essential ($V_T$ analysis)
  - Small MOSFET (2-D): Current reduction (surface, field mobility)
- Described PROPHET features for device modeling