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

Bryan A. Biegel

MRJ Technology Solutions

NASA Ames Research Center, NAS Division

Collaborators

Dr. Conor Raffertty (Lucent Technologies)

Dr. Zhiping Yu, Prof. R.W. Dutton (Stanford University)

Dr. Mario Ancona (Naval Research Laboratory)

biegel@nas.nasa.gov, http://science.nas.nasa.gov/~biegel

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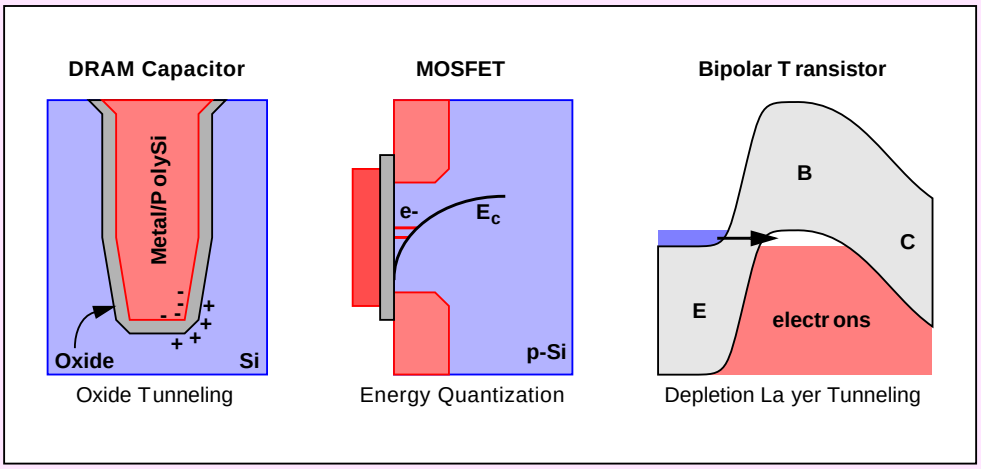
Outline

- **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):

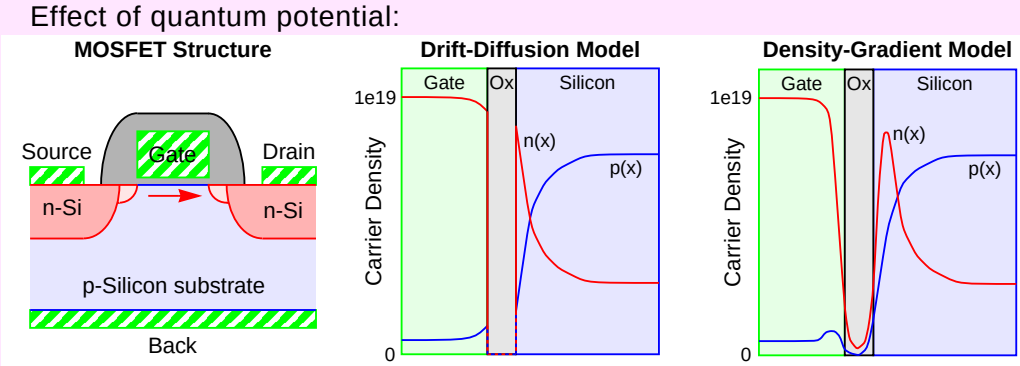
$$\frac{\partial n}{\partial t} = \nabla \cdot [D_n \nabla n - n\mu_n \nabla(u + u_{qn})]$$

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

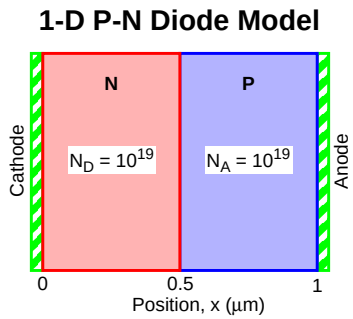
$$u_{qn} \equiv 2b_n\left(\frac{\nabla^2\sqrt{n}}{\sqrt{n}}\right) \qquad b_n \equiv \frac{-\hbar^2}{12m_n^* q}$$

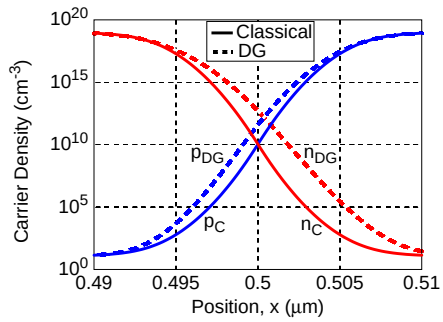
$$u_{qp} \equiv -2b_p\left(\frac{\nabla^2\sqrt{p}}{\sqrt{p}}\right) \qquad b_p \equiv \frac{\hbar^2}{12m_p^* q}$$

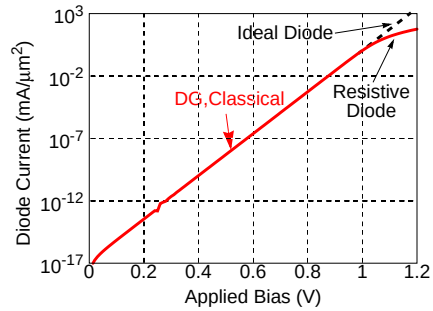
Effect of quantum potential:



P-N Diode (1-D)



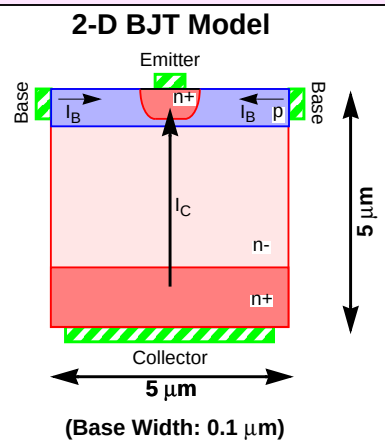


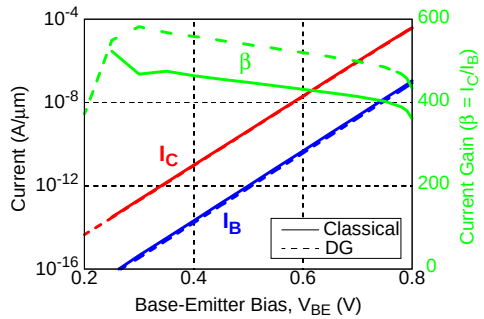


Conclusions:

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

Bipolar Junction Transistor (2-D)

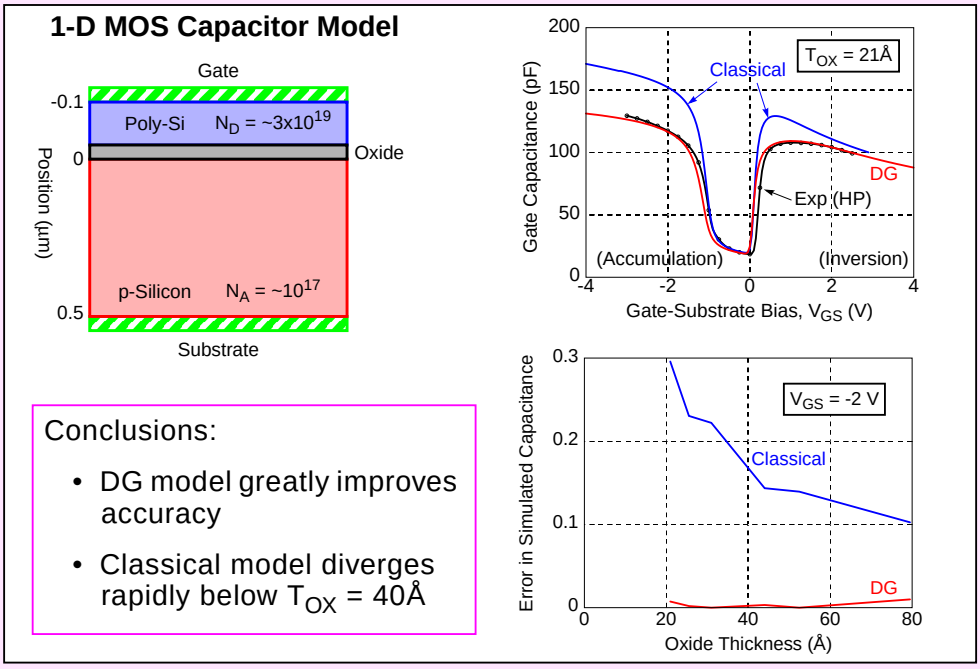




DG base current 20% *smaller* ⇒ DG current gain is *higher*

Quantum effects *improve* operation?

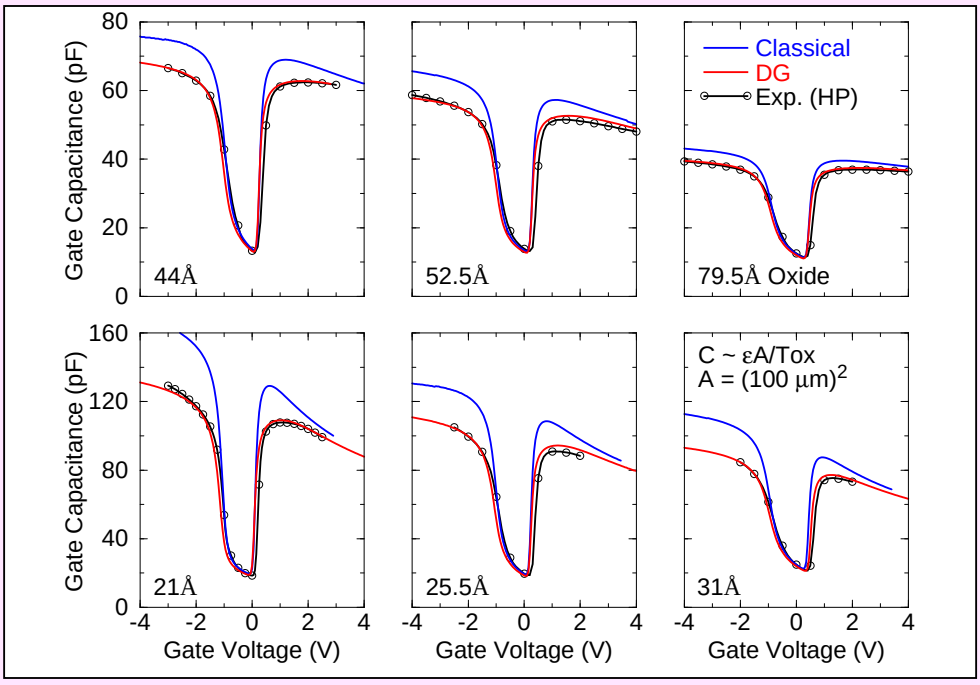
MOS Capacitor (1-D)



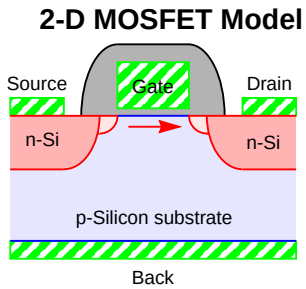
Conclusions:

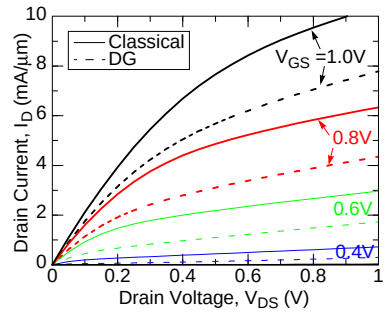
- DG model greatly improves accuracy
- Classical model diverges rapidly below T_{OX} = 40Å

MOS Capacitor Details



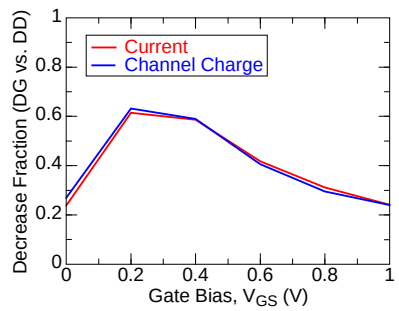
30 nm MOSFET (2-D)





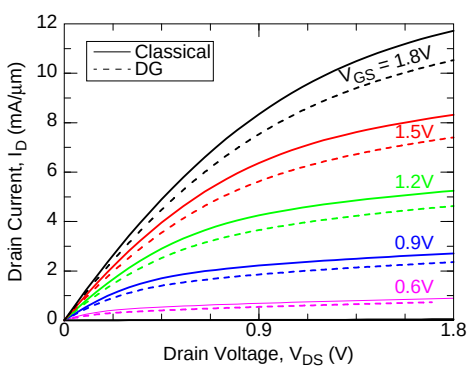
Conclusions:

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

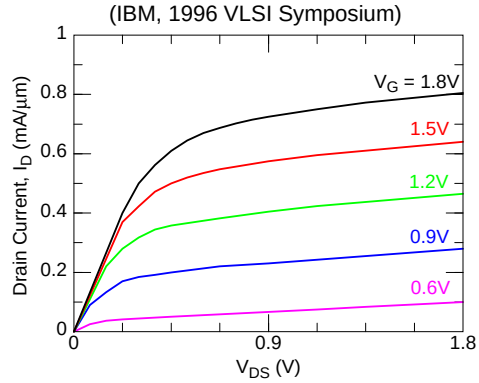


80 nm MOSFET vs. Exp. (2-D)

DG and Classical Simulations



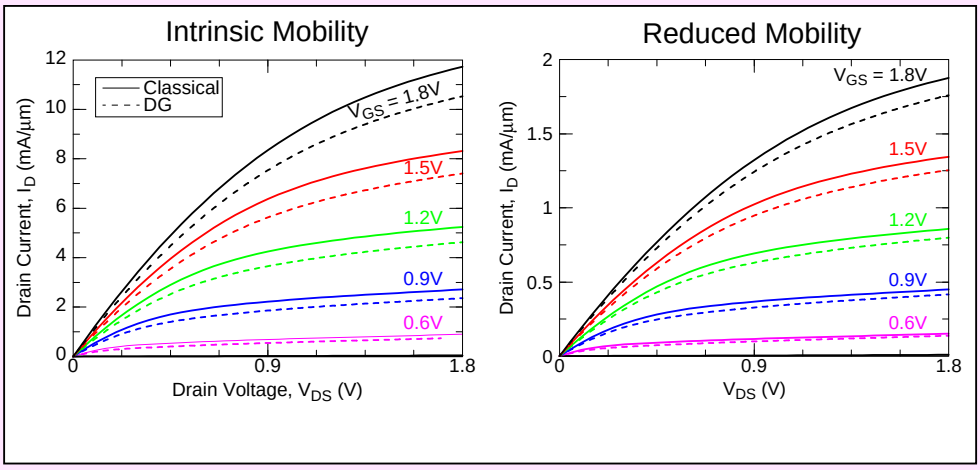
Experiment
(IBM, 1996 VLSI Symposium)



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

Ionized Impurity Scattering

Mobility model: $\mu_I = \mu_{min} + \dfrac{\mu_0 - \mu_{min}}{1 + (N/N_{ref})^{\alpha}}$



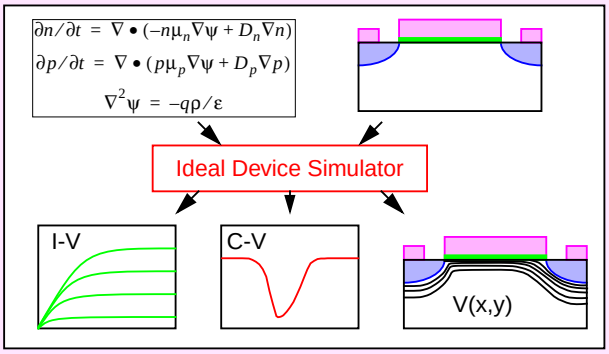
DG model works with position-dependent mobility

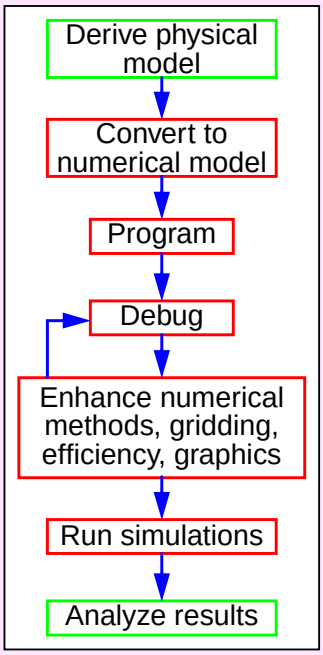
Transport Model Development Approach

Standard, single-model approach:

- Formulation to results-analysis is LONG
- Code structure restricts future enhancements
- Single-model code eventually discarded

PDE Solver Approach:





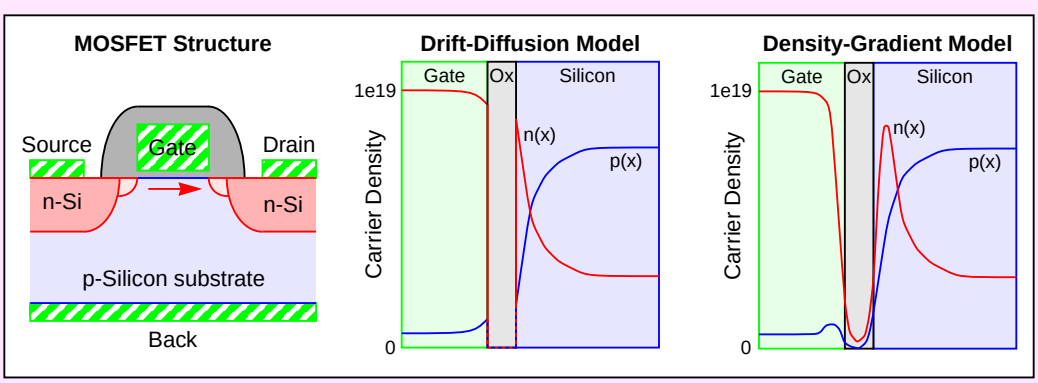
PROPHET PDE Solver

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: $\psi, n, p, \psi_{qn}, \psi_{qp}$
- Quasi-Fermi version of DG model: 1 month
  - Solution variables: $\psi, \phi_n, \phi_p, \sqrt{n}, \sqrt{p}$
- Ionized impurity scattering: 1 hour



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