Multi-Dimensional Quantum Tunneling and Transport Using the Density-Gradient Model

Bryan A. Biegel

MRJ Technology Solutions

NASA Ames Research Center, NAS Division

Collaborators

Dr. Zhiping Yu (Stanford University)

Dr. Mario Ancona (Naval Research Laboratory)

Dr. Conor Rafferty (Lucent Technologies)

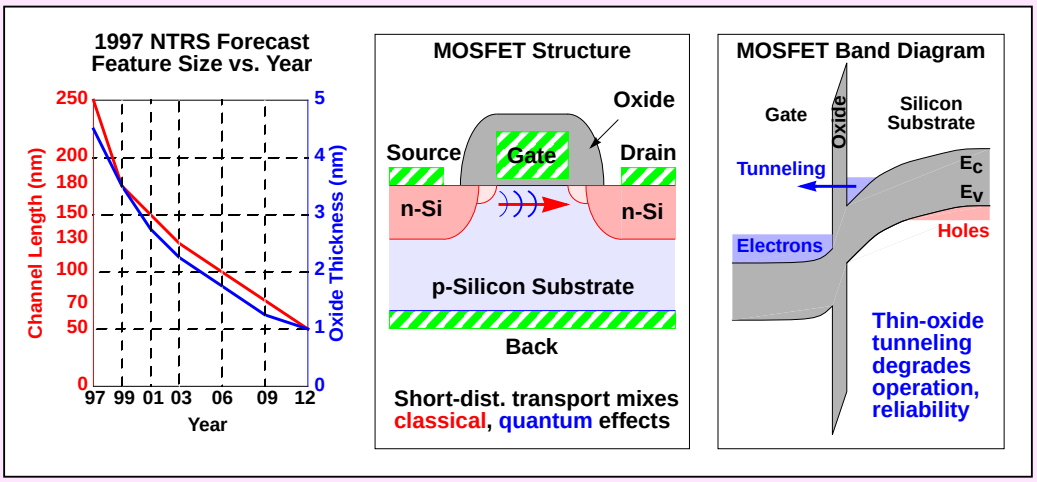
biegel@nas.nasa.gov, http://science.nas.nasa.gov/~biegel

Multi-Dimensional Quantum Tunneling and Transport Using the Density-Gradient Model

Outline

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

Tunneling and Transport in MOSFETs



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

Density-Gradient Model

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

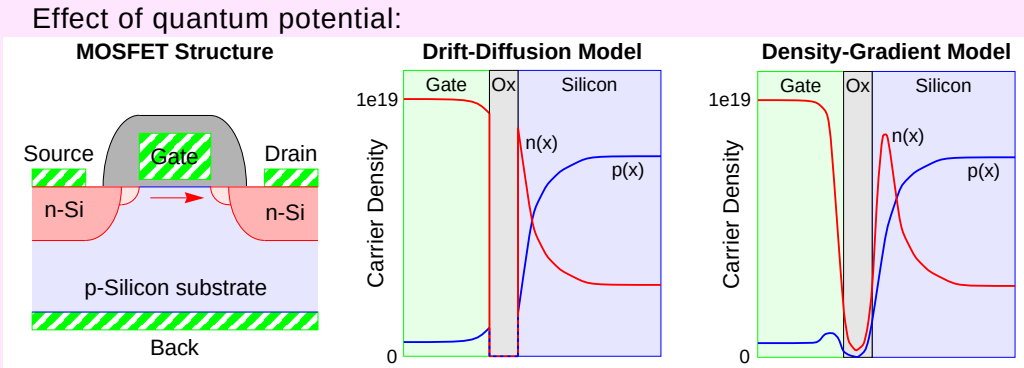
$$\frac{\partial n}{\partial t} = \nabla \cdot [D_n \nabla n - n\mu_n \nabla(u + u_{qn})]$$

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

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

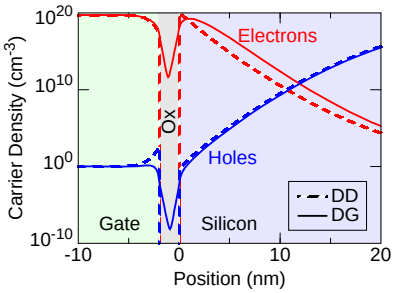
$$u_{qp} \equiv -2b_p\left(\frac{\nabla^2\sqrt{p}}{\sqrt{p}}\right) \qquad b_p \equiv \frac{\hbar^2}{12m_p^* q}$$

Effect of quantum potential:

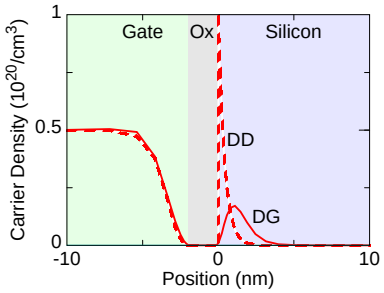


Quantum Confinement - Carrier Profiles

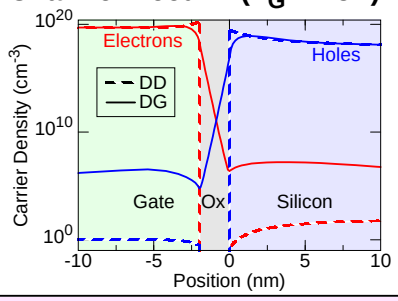
Channel Inversion (V_G=1V)



Channel Inversion (V_G=1V)



Channel Accum. (V_G=-1.5V)

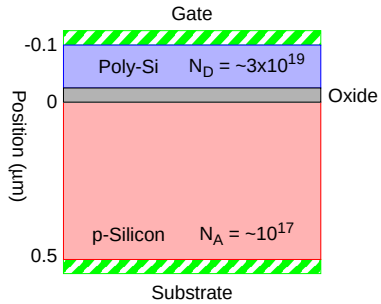


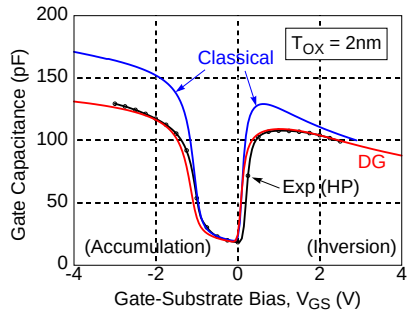
Conclusions:

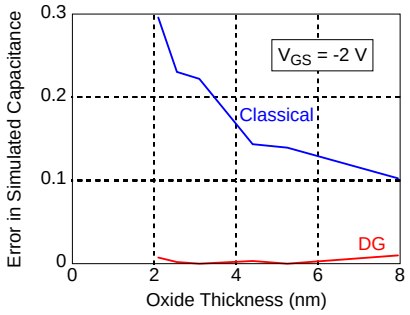
- Quantum confinement significantly changes inversion charge profile
- Densities decrease exponentially into oxide

MOS Gate Capacitance

1-D MOS Capacitor Model





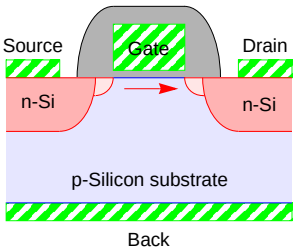


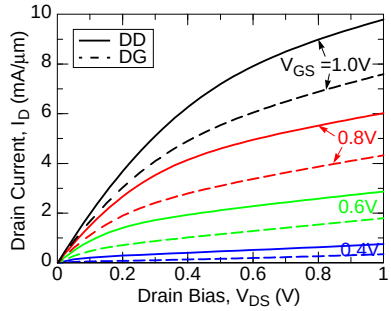
Conclusions:

- DG model greatly improves accuracy
- Classical model diverges rapidly below T_{OX} = 4nm

30 nm MOSFET - Drain Characteristic

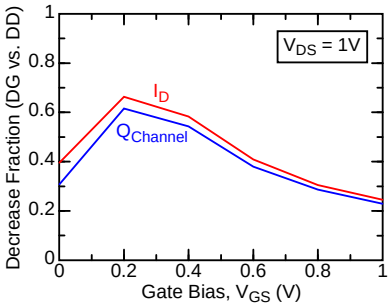
2-D MOSFET Model





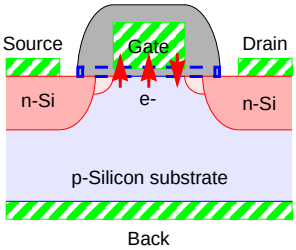
Conclusions:

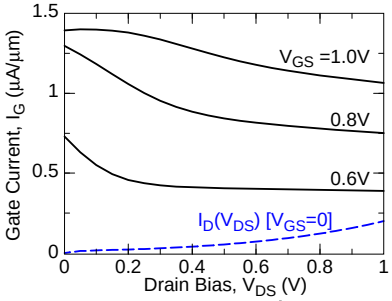
- MOSFET still works at 30nm channel length!
- Quantum effects reduce current by up to 60%
- Current decrease due to reduced channel charge



30 nm MOSFET - Gate Oxide Tunneling

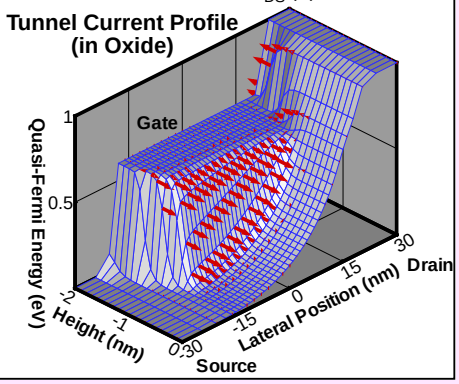
2-D MOSFET Model





Conclusions:

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



Conclusions

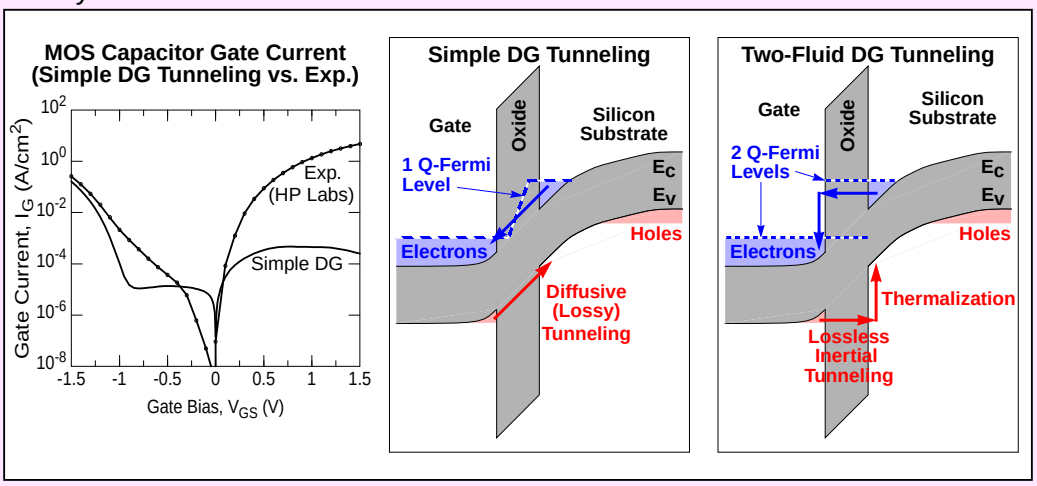
- Density-Gradient transport model:
  - Similar to industry standard model (DD)
  - Moderate additional computation
  - Quantum confinement, tunneling
- Simulated quantum effects
  - MOS Capacitor: dramatic improvement in accuracy
  - Small MOSFET: I_D decrease = $Q_{Channel}$ decrease
  - First 2-D 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)