Nanoscale Transistors: Device Physics, Modeling, and Simulation

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October 11, 2001

Silicon CMOS technology continues to drive progress in electronics, but device scaling is rapidly taking the metal oxide semiconductor field-effect transistor (MOSFET) to its limit. When MOS technology was developed in the 1960's, channel lengths were about 10 micrometers, but researchers are now exploring transistors with channel lengths on the 10 nanometer scale. A wide variety of new devices is also being explored as possible candidates to replace MOSFETs so that devices can continue to scale to molecular dimensions. Nanoscale MOSFET engineering, is, however, continues to be dominated by concepts and approaches originally developed to treat microscale devices. But to push MOSFETs to their limits and to explore devices that may complement or even supplant them, a clear understaqnding of device physics at the nano/molecular scale is essential.

This monograph was written for electrical engineers, physicists, chemists, and others who are engaged in work on nanoscale electronic devices. An understanding of basic semiconductor physics is assumed. Chapter 1 reviews some basic concepts, and Chapter 2 summarizes the essentials of traditional semiconductor devices, digital circuits, and systems. This material provides a baseline against which new devices can be assessed. At the same time, it defines the requirements of a device for it to be useful in an electronic system. Chapters 3 and 4 present a nontraditional view of the MOSFET using concepts that are valid at the nanoscale. By treating a traditional device from a fresh perspective, these chapters are designed to introduce electrical engineers to a ways of thinking about small electronic devices. For others, these chapters provide a deep understanding of the dominant electronic device. In Chapter 5, we apply the same concepts to the carbon nanotube FET as an example of how to apply the concepts to new devices and to explore a promising new device approach. Finally, in Chapter 6, we explore the limits of devices by discussing electrical conduction in single molecules.

My objective in writing this monograph is to provide engineers and scientists with the tools they need to push traditional electronic devices to their limits and to develop the new devices that will follow the MOSFET.

1) **Basic Concepts**

1.1 3D, 2D, 1D Carriers
1.2 DOS
1.3 carrier densities
1.4 directed moments
1.5 quantized conductance
1.6 semiclassical carrier transport
1.7 ballistic transport: semiclassical
1.8 ballistic transport: quantum

2) **Devices, Circuits and Systems**

2.1 The MOSFET
2.2 MOS Electrostatics
- The MOS capacitor
- MOSFET energy bands vs. bias
- 2D electrostatics: The geometrical scaling factor

2.3 MOSFET Current-Voltage Characteristics
- General expression
- Linear region current
- Saturation region current (long channel)
- Saturation region current (velocity saturated)
- Full-range (above threshold)
- Subthreshold

2.4 The bipolar transistor
- Device structure I-V
- MOSFET as a bipolar transistor

2.5 CMOS Technology
- The CMOS inverter and digital gates
- Device, circuit and system figures of merit
- MOSFET scaling
- Systems considerations

3) **The Ballistic MOSFET**

3.1 Mean-free-paths and L
3.2 Ballistic I-V (T > 0 nondegenerate)
3.3 Ballistic I-V (T = 0 degenerate)
3.4 Ballistic I-V (T > 0, general)
3.5 Numerical simulation of the ballistic MOSFET
3.6 Discussion

4) **Scattering Theory of the MOSFET**

4.1 I-V in terms of the transmission coefficient
4.2 The transmission coefficient
- low V_{DS}
- high V_{DS}

4.3 The mean-free-path for backscattering