Physics of the Ultimate Transistor: An Introduction to Electronics from the Bottom Up

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MOSFET scaling continues to take transistors to smaller and smaller dimensions while advances in nanoscience provide fascinating possibilities for new electronic technologies. Today, the MOSFET is a true mesoscopic device – one of enormous importance for computing, data storage, and for communications. The question of how far CMOS technology can be pushed continues to be an important one. In this tutorial, I will present a simple, physical model for the nanoscale MOSFET – one that can be related to traditional approaches in semiconductor devices but also to the new approaches that have been developed in mesoscopic and molecular electronics over the past 10-15 years [4, 5]. I'll argue that the smaller MOSFETs become, the easier they are to understand. I will use this simple model to project the limits of transistors. Finally, I'll conclude with some thoughts about 21st Century electronics. In the future, device technology must address a broad range of applications to contribute to the solution of global challenges such as energy, the environment, and healthcare. The nanoscale MOSFET provides a useful starting point for developing a new conceptual framework for electronics at the nanoscale, an approach that we call "Electronics from the Bottom Up" [6].

Figure 1 illustrates the essence of the approach. Modulating the height of an energy barrier controls current flow in most transistors. In a MOSFET, electrons are injected from the thermal equilibrium source reservoir over the top of the barrier and into the channel. The electron density at the top of the barrier is determined by MOS electrostatics. In a so-called, well-tempered MOSFET, the density at the top of the barrier is $Q_i(0) = C_G(V_{GS} - V_T)$ where C_G is the gate capacitance (the oxide capacitance in series with the semiconductor capacitance). Under on-current conditions (high gate and high drain bias) injected carriers diffuse across a thin bottleneck near the top of the barrier and are "collected" by the high-field portion of the channel. Since the current-limiting portion of the transistor is a low-field region into which thermal equilibrium electrons are injected, the on-current is controlled by low energy portions of the bandstructure and by low energy scattering processes. The result is that the near-equilibrium mobility determines the on-current even though strong off-equilibrium, hot carrier transport occurs across most of the channel.

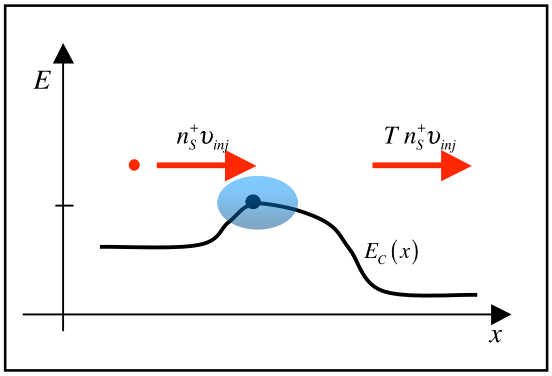

Fig. 1 Energy vs. position diagram for a nanoscale MOSFET. Electrons are injected from a thermal equilibrium source into a low-field region at the beginning of the channel. The high-field portion of the channel acts as a "collector."

The simple model presented in this tutorial (though developed when MOSFET channel lengths were ~250nm [1] continues to describe today's MOSFETs with channel lengths of 50 nm or less. It also provides a clear way to establish the scaling limits of transistors.

The simple model developed in this tutorial may also be viewed as a Landauer model for a MOSFET, appropriately generalized to include high bias, inelastic scattering, and MOS electrostatics. From that perspective, it provides a natural starting point for examining nanoelectronic devices more generally. We will briefly convey the spirit of this approach and how it is generalized into the non-equilibrium Green's function (NEGF) formalism for quantum transport in nanostructures [4].

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