

Quantum Transport in a 12-nm MOSFET Using FDTD

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Abstract—Quantum transport is investigated in an N-channel enhancement metal-oxide-semiconductor field-effect transistor (MOSFET). With the presence of tunneling potential distributions in a 12-nm channel, transmission functions and Fermi-Dirac distributions with different external drain-source and gate-source voltages are obtained. Current-voltage characteristics of the MOSFET are calculated based on the transmission functions and Fermi-Dirac distributions. To unveil the essence of current generations in the MOSFET channel, wave nature of electrons in nanoscale devices are simulated using the finite-difference time-domain (FDTD) method. The electron wavefunction is assumed to be a sinusoidal wave in a Gaussian envelope. Electron scattering through different potential distributions in the 12-nm channel is explored through FDTD numerical simulations.

I. INTRODUCTION

Moore's law has played a pivotal role in accelerating the growth of the semiconductor industry since 1965 [1]. It forecasts a rising trend in the number of components on integrated circuits, initially doubling annually, but later revised in 1975 to doubling every two years [2]. The trend of doubling has slowed in the past five years, as transistor sizes approach the quantum regime. Although the marketing term node range has been predicted to reduce by half in six years from 3 nm in 2022 to 1.5 nm in 2028, the corresponding physical gate length and gate pitch will decrease from 18 nm to 12 nm and from 48 nm to 42 nm respectively, which is far below the prediction of doubling every two years made in 1975 [3]. Furthermore, the predicted gate length in 2031 would remain as 12 nm, which is the same as that in 2028 [3]. This indicates that the classical semiconductor theory and classical transport are approaching their limits. To break the limits, further reduce the size of each transistor, and increase the total number of components on an integrated circuit, it is crucial to understand the fundamental physics and consider the wave-like behavior of electrons in nanoscale semiconductor devices, which has been explored in [4] and [5]. In [4], a thorough review of quantum transport has been conducted to support the integration of quantum techniques into the future advancement of semiconductor devices. Quantum effects such as confinement, interference, and tunneling are increasingly relevant in modern field-effect transistors, significantly impacting device performance and requiring advanced quantum transport methods for accurate modeling and simulation. In [5], to make connections between electromagnetics (EMs) and quantum transport, comparisons between computational EMs and quantum transport using FDTD have been explored. Current-voltage characteristics and FDTD simulations of electron scattering in a 12-nm metal-

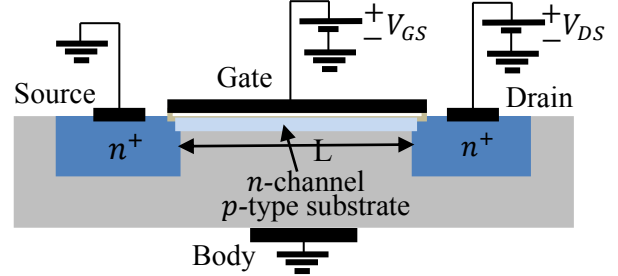


Fig. 1. An N-channel enhancement metal-oxide-semiconductor field-effect transistors (NMOS) with a channel length of L , where the source and body terminals are connected to the ground and the gate and drain terminals are connected to external DC sources.

oxide-semiconductor field-effect transistors (MOSFETs) will be presented.

II. QUANTUM TRANSPORT

Fig. 1 illustrates a 1D n-channel enhancement MOSFET with a channel length of L . It is assumed that no concentration gradients and diffusion length are present. The channel length is considered equal to the gate length. Once a channel is established, the channel current I flows from the drain to the source, driven by electrons moving in the opposite direction. For an electron with charge $Q(x, t)$ and wavefunction $\psi(x, t)$ in the 1D channel, the channel current I is determined by the change rate of the charge over time [6],

$$I = \frac{\partial Q(x, t)}{\partial t} = -q \int \frac{\partial}{\partial t} |\psi(x, t)|^2 dx \quad (1)$$

where the elementary charge $q = 1.602 \times 10^{-19}$ C. Based on the 1D time-dependent the Schrödinger equation,

$$\frac{\partial}{\partial t} \psi(x, t) = \frac{i\hbar}{2m_e} \frac{\partial^2 \psi(x, t)}{\partial x^2} - \frac{i}{\hbar} V(x) \psi(x, t) \quad (2)$$

where the reduced Planck's constant $\hbar = \frac{h}{2\pi} = 6.582 \times 10^{-16}$ eV · s (eV denotes electron voltage), the mass of electron $m_e = 9.109 \times 10^{-31}$ kg, V is the potential function across the channel. With multiple steps of rigorous derivations, the channel current can be represented by,

$$I = \frac{q}{2\pi\hbar} \int_{-\infty}^{\infty} dE \cdot T(E) (f_1 - f_2) \quad (3)$$

where the transmission function $T(E)$ is the probability that an electron crosses the channel as a function of energy, and f_1 and

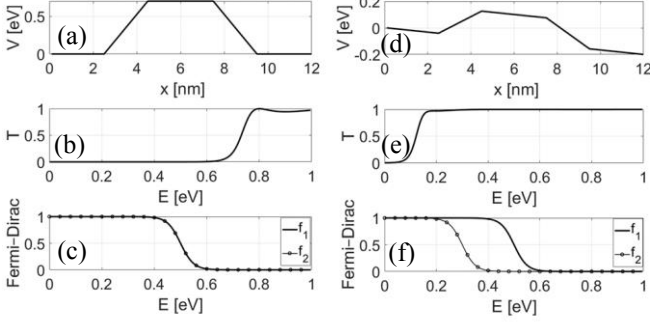


Fig. 2. (a) The tunneling potential distribution, (b) transmission matrix, and (c) Fermi-Dirac functions in a silicon-based 12-nm channel with $V_{GS} = 0$ V and $V_{DS} = 0$ V. (d) The tunneling potential distribution, (e) transmission matrix, and (f) Fermi-Dirac functions in a silicon-based 12-nm channel with $V_{GS} = 0.5$ V and $V_{DS} = 0.2$ V. Assume that the barrier potential is 0.7 eV and the Fermi level at the source is 0.5 eV.

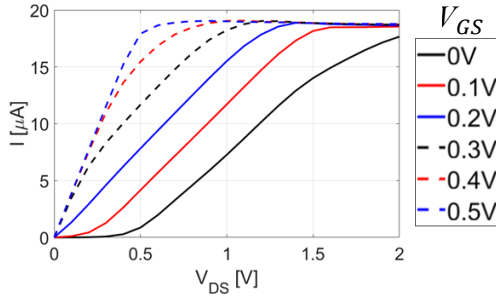


Fig. 3. IV characteristics of a silicon-based NMOS as a function of V_{GS} and V_{DS} with a channel length of 12 nm.

f_2 are the Fermi-Dirac distributions. Current-voltage characteristics of the 12-nm MOSFET are obtained from (3).

Based on (2), split $\psi(x, t)$ into the real and imaginary components and the corresponding 1D FDTD representation can be obtained,

$$\begin{aligned} \psi_{real}^{m+1}(n) &= \psi_{real}^m(n) - \frac{\hbar}{2m_e} \frac{\Delta t}{\Delta x^2} [\psi_{imag}^{m+1/2}(n+1) - \\ &2\psi_{imag}^{m+1/2}(n) + \psi_{imag}^{m+1/2}(n-1)] + \frac{\Delta t}{\hbar} V(n) \psi_{imag}^{m+1/2}(n) \end{aligned} \quad (4a)$$

$$\begin{aligned} \psi_{imag}^{m+3/2}(n) &= \psi_{imag}^{m+1/2}(n) + \frac{\hbar}{2m_e} \frac{\Delta t}{\Delta x^2} [\psi_{real}^{m+1}(n+1) - \\ &2\psi_{real}^{m+1}(n) + \psi_{real}^{m+1}(n-1)] - \frac{\Delta t}{\hbar} V(n) \psi_{real}^{m+1}(n) \end{aligned} \quad (4b)$$

where m is the time index, n is the spatial index, and Δt and Δz are the step sizes in time and spatial domains, respectively. Note that the imaginary parts of ψ in the time domain are shifted by half a discretized cell in the numerical domain of interest.

III. NUMERICAL SIMULATIONS

Fig. 2(a) shows the trapezoid-shaped tunneling barrier potential distribution V of the 12-nm n-channel enhancement metal-oxide-semiconductor field-effect transistors (NMOS) when there are no external drain-source and gate-source voltages $V_{GS} = 0$ V and $V_{DS} = 0$ V. Fig. 2(b) presents the transmission function $T(E)$. The transmission is 0 when the normalized energy level is less than approximately 0.7, showing that the electrons without enough energy cannot pass through the channel. Fig. 2(c) presents the Fermi-Dirac

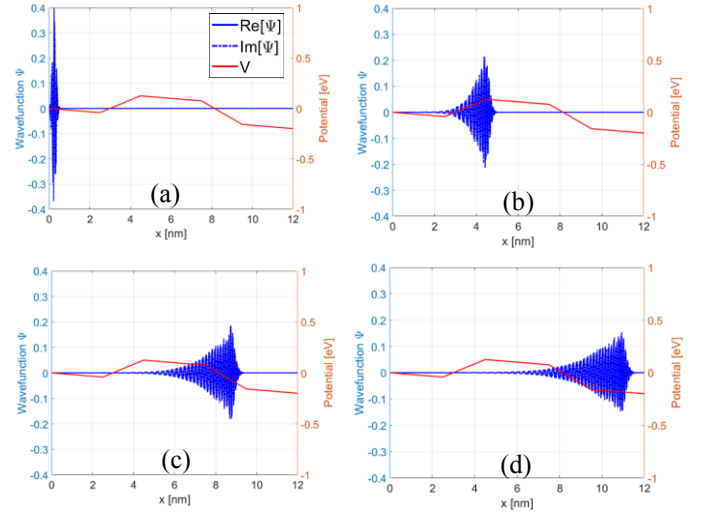


Fig. 4. FDTD simulations of electron forward scattering through the 1D 12-nm NMOS with $V_{GS} = 0.5$ V and $V_{DS} = 0.2$ V at (a) 0 fs, (b) 1 fs, (c) 2 fs, and (d) 2.5 fs. The solid blue lines show the real component of the wavefunction, the dashed blue lines show the imaginary component of the wave function, and the red lines show the tunneling barrier of the NMOS.

distributions on both sides of the NMOS, which are identical due to $V_{DS} = 0$ V. Fig. 2(d)-2(f) present the tunneling barrier potential distribution V , the transmission function $T(E)$, and the Fermi-Dirac distributions when $V_{GS} = 0.5$ V and $V_{DS} = 0.2$ V. Observe that the tunneling barrier potential will be lowered and the electrons with lower energy tend to pass through the channel when increasing V_{GS} and V_{DS} . Fig. 3 shows current-voltage (IV) characteristics of the 12-nm NMOS, which is obtained from (3) and different from the classical NMOS. The barrier voltage will not affect the channel formation when $V_{GS} = 0$ V and V_{DS} is large enough. Fig. 4 presents FDTD simulations of electron forward scattering, where the electron can pass through the 12-nm channel when $V_{GS} = 0.5$ V and $V_{DS} = 0.2$ V.

IV. CONCLUSION

The channel current in a nanoscale field-effect transistor has been presented to validate the difference from that in the classical transistor. FDTD simulations of the electron's wave nature explains the behavior of channel current formation. Details of quantum transport in the 12-nm MOSFET using FDTD will be discussed in the presentation.

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