ARAB ACADEMY FOR SCIENCE, TECHNOLOGY AND MARITIME TRANSPORT
College of Engineering and Technology
Electronics and Communications Engineering

# Analysis and modeling of a Single-Electron Transistor ( SET )

A Thesis
Submitted in Partial Fulfillment to the Requirements
for the Master's Degree in
**Electronics and Communications Engineering**

**By**
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**Arab Academy for Science, Technology and Maritime Transport - Alexandria**

**AUGUST 2006**

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## Abstract

The wide range for applications for microelectronic devices is basically due to the scaling down of dimensions of such devices. Unfortunately, the scaling down and miniaturization of these devices is not infinite. There are some challenges and limitations for scaling down of these devices into the nanometer regime.

Accordingly, researchers are looking now to build new microelectronic devices with very small dimensions (nanotechnology). The behavior of such devices will be interpreted based on quantum mechanics principles due to small dimensions. The single-electron transistor (SET) is one of these devices which belongs to the quantum microelectronics family.

The thesis is organized as follows:

Chapter 1: The motivation behind searching for new electronic devices to be used in the nanometer regime, revision of the challenges facing conventional CMOS devices and revision of the promising nanotechnology devices.

Chapter 2: The promising applications for SET devices: hybrid, room-temperature, logic and novel circuits.

Chapter 3: The physics and operation of the single-electron transistor (SET) including different theories used to describe the transport of electrons within the device and the Coulomb blockade phenomenon.

Chapter 4: The models used to simulate the SET including master equation method, Monte-Carlo method, SPICE models and computer programs used for each method.

Chapter 5: Our contribution of building a new fast and accurate model for SET devices using the reduced master equation method, also we will benchmark our results with that of "Quantum-Transport Group" at Delft university.

Chapter 6: Conclusions and proposed future work.

# Contents

# List of Symbols

| *Symbol* | **Description** | **Units** |
|---|---|---|
| *Å* | Angstrom | |
| $C_B$ | Capacitance of Back-Gate Capacitor in SET | F |
| $C_D$ | Capacitance of Drain Tunnel Junction in SET | F |
| $C_G$ | Capacitance of Gate Capacitor in SET | F |
| $C_S$ | Capacitance of Source Tunnel Junction in SET | F |
| $D_f(E)$ | The Density of States of the Final Side of the Potential Barrier. | $m^{-3}J^{-1}$ |
| $D_i(E)$ | The Density of States on the Initial Side of the Potential Barrier. | $m^{-3}J^{-1}$ |
| $E$ | Electric Field | V/m |
| $E$ | Electron Charge | C |
| $E_c$ | Charging Energy of Electron | eV |
| $E_{c,f}$ | The Conduction Band Edge of the Side where the Electrons is Tunneling to. | eV |
| $E_{c,i}$ | The Conduction Band Edge of the Side where the Electron Resides Initially. | eV |
| $E_f$ | Final Energy of a Tunneling Electron. | ev |
| $E_i$ | Initial Energy of a Tunneling Electron. | ev |
| $f(E)$ | Fermi–Dirac Distribution Which gives the Occupation Probability of Energy Levels in Equilibrium | - |
| $g_m$ | Transconductance | S |
| $H$ | Plank's Constant = 6.626E-34 | Js |
| $\bar{h}$ | Modified Plank's Constant = $h/2\pi$ = *1.055E-34* | Js |
| $I$ | Current | A |
| $K$ | Constant Field Scaling Factor | - |
| $K_B$ | Boltzman Constant = 1.381E-23 | J/K |
| $k_i$ | Momentum of State i | Kg m/s |
| $N$ | Number of Free Electrons | - |
| $P_i(t)$ | Time Dependent Occupation Probability of State i | - |
| $p_n$ | The Occupation Probability of the State *n* | - |

| *Symbol* | **Description** | **Units** |
|---|---|---|
| $P_{th}$ | Threshold Probability | - |
| $R_D$ | Resistance of Drain Tunnel Junction in SET | Ω |
| $R_S$ | Resistance of Source Tunnel Junction in SET | Ω |
| $R_T$ | Tunneling Resistance | Ω |
| $T_{if}$ | Tunnel Transmission Coefficient from State *i* to a State *f* | - |
| $V$ | Voltage | V |
| $V_B$ | Back-Gate Voltage for SET | V |
| $V_{DD}$ | Drain Bias Voltage for SET | V |
| $V_G$ | Gate Voltage for SET | V |
| $V_{th}$ | Threshold Voltage for SET | V |
| $Z`$ | Total Capacitance of SET | F |
| $\Gamma_{i\to f}$ | The Tunnel Rate from an Initial State *i* to a Final State *f*. | 1/s |
| $\Gamma_{ij}$ | Tunnel Rate From State j to State i | 1/s |
| $\Gamma(n-1/n)$ | The Tunneling Rate From State *n* to State *n-1* | 1/s |
| $\Delta E$ | Quantum Level Spacing | eV |
| $\Delta F$ | Change in Free Energy in SET | eV |
| $\Delta V$ | The Voltage Difference across the Tunnel Junction. | V |
| $\tau$ | Tunnel Time | s |

# List of Acronyms

| | |
|---|---|
| 2-D | Two Dimensional |
| ASIC | Application Specific Integrated Circuit |
| BiCMOS | Bipolar CMOS |
| BJT | Bipolar Junction Transistor |
| CMOS | Complementary Metal Oxide Semiconductor |
| *dna*SET | Deoxyribonucleic acid SET |
| DRAM | Dynamic Random Access Memory |
| FET | Field-Effect Transistors |
| ITRS | International Technology Roadmap for Semiconductors |
| KOSEC | Korea Single Electron Circuit Simulator |
| LTG | Linear Threshold Gate |
| MC | Monte-Carlo |
| ME | Master Equation |
| MIPS | Millions of Instructions per Second |
| MOS | Metal Oxide Semiconductor |
| MOSES | Monte-Carlo Simulator for Single-Electron Systems. |
| MOSFET | Metal-Oxide Semiconductor Field-Effect Transistor |
| MPU | Microprocessor Unit |
| MTJ | Multiple-Tunnel Junction |
| nMOS | n-channel MOSFET |
| NRSC | National Radio Science Conference |
| NVM | Non-Volatile Memory |
| pMOS | p-channle MOSFET |
| QD | Quantum Dot |
| QT | Quantum Transport |
| *rf* | Radio Frequency |
| RNG | Random-Number Generator |
| SEM | Scanning Electron Microscopy |
| SENECA | Single Electron Nano-Electronic Circuit Analyzer |
| SET | Single-Electron Transistor |
| SIA | Semiconductor Industry Association |

| | |
|---|---|
| SIMON | **SIM**ulation **O**f **N**anostructures |
| SoC | System on Chip |
| ssDNA | Single-Stranded DNA |
| STM | Scanning Tunneling Microscope |
| ULSI | Ultra-Large Scale Integration |

# List of Figures