Novel Hybrid SETMOS Logic for Ultra-low-power Applications

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Novel Hybrid SETMOS Logic for Ultra-low-power Applications

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Abstract This paper investigates the Single-Gate Single Electron Transistors (SG-SETs) based hybrid SETMOS logic circuits for ultra-low-power applications at room temperature. The methodological design of the proposed hybrid SETMOS logic circuits is compatible with 22-nm CMOS bias and process. The widely acclaimed Mahapatra-Ionescu-Bannerjee (MIB) model is modified to implement the proposed SG-SET and hybrid SETMOS logic circuits using Verilog-A. Logic inverter, two-input NAND, NOR, AND, OR, EX-OR, and EX-NOR logic gates are simulated at room temperature using novel SETMOS hybridization. The proposed work is compared with the 22-nm CMOS counterpart (simulated with the same setup). We found that the reduction in total power dissipation by 98.04%, 96.45%, 94.65%, 93.7%, 92.63%, 93.52%, 95.57% using hybrid SETMOS NAND, NOR, AND, EX-OR and EXOR gates than 22 nm CMOS logic gates. The proposed work is compared with other works of literature. We also examined the robustness of the proposed logic circuits against temperature variations from 77 K to 500 K.

Keywords Coulomb-Blockade · MIB-Model · Quantum-Mechanical-Tunneling · SETMOS-Hybridization · Silicon-Single-Electron-Transistor · Ultra-Low-Power-Circuits

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1 Introduction

Beyond-Complementary Metal Oxide Semiconductor (CMOS) nanodevices have been investigated remarkably for ultra-low-power applications for many years, essentially for CMOS extension and replacement. The degradation in the CMOS performance begins by virtue of technology scaling. The requirement of ultra-low-power dissipation in applications is of the utmost demand. This process eventually opens the door for novel nanodevices to succeed CMOS or hybridize with existing technology. In the era of nanoelectronics, Single Electron Transistors (SETs) can be the most promising nanodevice for logic as well as memory applications [1, 2]. SET is working on quantum physics principles: Coulomb Blockade (CB) and Quantum Mechanical Tunneling (QMT) [3, 4]. The low current drive, low supply voltage, small critical dimensions due to aF range total capacitance, and room temperature operations were the issues for CMOS compatibility [5–8]. However, the past two decades witnessed significant research work to attain and overcome many of these issues [8–18]. Research to exhibit room temperature behavior analogous to a conventional MOSFET and its demonstration for application in logic and memory circuits is still in infancy. The proper design methodology from device-level engineering to circuit design is a need. The advantage of silicon processing further enhancing the SET to hybridize with existing CMOS for ultra-low-power dissipation without losing the functionality [9, 11, 19, 20].

In our previous work, we have explored many hybridization techniques, and we ascertained that the Single Gate SET (SG-SET) as pull-down network and P-type MOS (PMOS) as pull-up network technique shows the best result in terms of ultra-low-power consumption and higher speed than contemporary techniques [20]. The CMOS compatibility and silicon processes are also advantages [20]. This hybridization method gives ultra-low-power consumptions than CMOS

and lesser propagation delay than other SETMOS hybridization techniques [20, 21]. Also, using this kind of hybridization, co-tunneling can be avoided compared to SET-only based circuits [6]. Our earlier work also comprises the device planning and optimization of SG-SET using TCAD simulation, observing CB and QMT at room temperature, and mathematical modeling to express the drain current using Gibbs free energy [21, 22]. The tunnel resistance, R_T is also extracted as 20 M Ω . This high range of R_T ($> h/e^2$) also ensures localization of electrons [6]. Hence, there are no assumptions made for any parameters in the proposed design. Experimental results imply that stray charges have less influence on silicon single-electron devices due to the charge screening effect compared to metal single-electron devices [23].

In this work, the logic circuits using the proposed technique are investigated for their applicability in ultra-low power applications. The novel hybrid SETMOS logic is implemented in Cadence Virtuoso using modified MIB of SG-SET and 22 nm PMOS predictive technology model (PTM) model [24, 25]. The logic inverter and two input NAND, NOR, AND, EX-OR, EX-NOR gates are simulated at room temperature. Similarly, the 22-nm CMOS logic gates are simulated using the same simulation set-up to compare the total power consumption. The hybrid logic circuits are also compared with other works of literature, and then the thermal analysis is done for 77 K, 150 K, 300 K, and 500 K temperatures.

2 Simulation Methodology

Fig. 1a shows the SG-SET structure with its critical dimensions simulated in TCAD [21]. The tunnel barrier optimization and island engineering techniques have been carried out to obtain the best dimensions and materials for tunnel junctions and island of SG-SET [19, 21, 26]. The room-temperature output characteristic is plotted and then calibrated with fabricated devices, as shown in Fig. 1b. The CB of ± 0.8 V is observed from the characteristics. Also, the calibration shows good compatibility with fabricated devices as CB voltage and the range of drain current is similar. Fig. 2a shows the symbol and RC model of SG-SET. The SG-SET parameters are evaluated based on the criteria of room temperature operation, and CMOS bias compatibility [21]. The gate capacitance calculated from CMOS bias ($e/2V_{DD}$) is 0.1 aF. The tunnel junction capacitance is calculated from the parallel plate model as 0.0468 aF [21] from TCAD simulations. This gives total capacitance ($C_T = C_G + 2C_J$) of 0.193 aF [21]. This also manifests the electrostatic energy ($E_C = e^2/C_T$) [5, 10, 18–20, 26, 27] nearly 32 times higher than room temperature energy. The electrostatic energy (E_C) of SET should be 30-40 times higher than thermal energy for logic and 10-20 times higher for memory application to avoid

Fig. 1: SG-SET (a) structure and its critical dimensions [21] (b) Output characteristics at room temperature and calibration with fabricated SETs

Fig. 2: SG-SET (a) RC model (b) output characteristics and (c) transfer characteristics ; at room temperature

thermal conduction [10, 20, 27]. The Mahapatra-Ionescu-Bannerjee (MIB) model [10], which is widely adopted for SET, is modified for SG-SET. The Verilog-A interface is used to implement SG-SET in Cadence Virtuoso for simulation. The modified MIB model is used to validate the TCAD results and gives accurate extraction of the tunnel resistance (20 M Ω) [21]. Fig.2b and Fig.2c show the output and transfer characteristics plotted at room temperature. The output characteristics clearly observed the CB for ± 0.8 V for zero gate voltage and then QMT overhauls CB [21]. The Coulomb oscillations analyzed in the transfer characteristics which is the signature property of the device. The gap of oscillation is 1.6 V which gives the gate capacitance of 0.1 aF; similar to estimated theoretically [21].

2.1 Simulation Method of Novel Hybrid SETMOS

Fig.3a shows the hybrid SETMOS logic inverter. For the logic inverter, the load capacitance is 30 aF calculated by summing intrinsic and extrinsic capacitances [21, 28]. Fig.3b shows the transient analysis simulated with a 100 MHz clock signal that verified the functionality of the inverter. The extracted total power dissipation is 3.11 nW. Fig.3c shows the

Fig. 3: (a) SETMOS inverter design using SET ($C_G=0.1$ aF, $C_{TD}=C_{TS}=0.0468$ aF and $R_T=20$ M Ω) and PMOS ($W=55$ nm, $L=22$ nm) (b) Transient characteristics (c) Voltage transfer characteristics [21]

voltage transfer characteristics of the inverter [21] with noise margin parameters.

Fig.4 illustrates the designs of the two-input NAND, NOR, EX-OR, EX-NOR, OR, and AND logic gates. The logic gates have the same architecture in which the pull-down network is the proposed SG-SET, and the pull-up network is 22-nm PMOS [24]. For OR and AND gate, SETMOS inverter is used to invert the logic of NOR and NOR.

The transient analysis verified the logic functionality of all gates, as shown in Fig.5. NAND, NOR, OR, and AND gates are simulated with 10 MHz, while EX-OR and EX-OR gates are simulated with 4 MHz operating frequency. The bias voltage of logic gates is 0.8 V. The propagation delay and total power dissipation are extracted from the simulation result.

Fig. 4: Hybrid SETMOS two input (a) two input NAND and AND (b) OR and NOR (c) EX-OR and EX-NOR logic gates

Fig. 5: Transient simulation of hybrid SETMOS two input (a) NAND, AND, NOR and OR (b) EX-OR and EX-NOR, logic gate circuits

3 Result and Discussion

Two input NAND, NOR, AND, OR, EX-OR, and EX-NOR gates using 22 nm CMOS are simulated at room temperature with the same bias (0.8 V) and operating frequency as hybrid SETMOS logic gates. Table.1 and Table.2 show the extracted propagation delay and total power dissipation along with the number of devices used for designing hybrid SETMOS and CMOS logic gates, respectively. From Table 1 and Table 2, we noted that the total power dissipation of hybrid SETMOS gates is very less than CMOS logic gates at the cost of propagation delay. The comparison of hybrid SETMOS logic gates with CMOS counterpart pointed to the decline in total power dissipation is 98.04%, 96.45%, 94.65%, 93.7%, 92.63%, 93.52%, 95.57% for NOT, NAND, NOR, AND, OR, EX-OR, and EX-NOR gates, respectively. Hence, this technique is more beneficial for ultra-low-power applications. The novel hybridization logic circuits results

Table 1: Extracted Parameters of Hybrid SETMOS Logic Gates at Room Temperature ($V_{DD}=0.8$ V)

Logic gate	Total Power @ 10 MHz	Propagation Delay	No. of Devices	
			SET	PMOS
NOT	3.11 nW	8.9 ns	1	1
NAND	1.4 nW	12.08 ns	2	2
NOR	4.46 nW	3.27 ns	2	2
AND	3.21 nW	12.09 ns	5	5
OR	7.47 nW	4.067 ns	5	5
EX-OR	8.68 nW	21.16 ns	6	6
EX-NOR	9.44 nW	18.26 ns	6	6

Table 2: Extracted Parameters of CMOS Logic Gates at Room Temperature ($V_{DD}=0.8$ V)

Logic gate	Total Power @ 10 MHz	Propagation Delay	No. of Devices	
			NMOS	PMOS
NOT	159.92 nW	54.85 ps	1	1
NAND	39.5 nW	1.31 ns	2	2
NOR	83.44 nW	1.28 ps	2	2
AND	48.24 nW	559.12 ps	5	5
OR	101.36 nW	4.94 ps	5	5
EX-OR	134 nW	559.0 ps	6	6
EX-NOR	213.52 nW	532.3 ps	6	6

Table 3: Comparison with Other Research Work at Room Temperature ($V_{DD}=0.8$ V)

Reference	Total Power Consumption				
	NOT	NAND	NOR	EX-OR	EX-NOR
Venkataratnam, (2008 [29])	2.11 μ W	0.78 μ W	4.14 μ W	1.5 μ W	1.5 μ W
Parekh, (2012 [27])	4 nW	-	-	-	-
Jana, (2013 [30])	3.877 nW	-	-	-	-
Abulateb, (2015 [31])	-	15.64 nW	15.64 nW	17.36 nW	-
Chaudhri, (2019 [32])	2050 nW	-	-	-	-
Proposed Work, (2021)	3.11 nW	1.4 nW	4.46 nW	8.68 nW	9.44 nW

are also compared with the other simulated SET and CMOS hybridization simulations [27, 29–32] at same bias (0.8 V) as shown in Table 3. The comparison explicates that the proposed logic gates' total power consumption is less than other hybridization methods at the same bias voltage.

4 Thermal analysis of Proposed Hybrid SETMOS Logic Circuits

The designed logic gates are further simulated at 77 K, 150 K, 300 K, 400 K and 500 K. Fig.6 shows the test bench circuit to simulate the logic circuit for different temperatures.

This wide range of temperature is considered to observe the thermal robustness of the proposed logic gates. The transient simulation for all logic gates has been performed at these temperatures. The propagation delay and total power dissipation are calculated from the simulation results.

CUT: Circuit Under test
Temperature: {77K, 150 K, 300 K, 400 K, 500 K}
Power Dissipation = $I_{avg} * V_{DD}$
Propagation Delay = $1/\text{Output Frequency}$

Fig. 6: Test bench for thermal analysis of hybrid SETMOS logic gates

Table 4: Thermal analysis effect on total power consumption

Logic Gate	Temperature				
	77 K	150 K	300 K	400 K	500 K
NOT	3.88 nW	3.95 nW	4.47 nW	4.98 nW	5.22 nW
NAND	1.21 nW	1.23 nW	1.4 nW	1.54 nW	1.71 nW
NOR	3.39 nW	3.63 nW	4.46 nW	4.82 nW	6.096 nW
EX-OR	7.63 nW	7.79 nW	8.84 nW	9.85 nW	11.52 nW
EX-NOR	7.68 nW	7.89 nW	8.94 nW	9.94 nW	11.416 nW
AND	7.12 nW	7.3 nW	7.47 nW	8.032 nW	9.48 nW
OR	1.40 nW	1.64 nW	2.84 nW	3.92 nW	5.016 nW

Table 5: Thermal analysis effect on propagation delay

Logic Gate	Temperature				
	77 K	150 K	300 K	400 K	500 K
NOT	8.32 ns	8.37 ns	7.67 ns	7.75 ns	6.06 ns
NAND	12.92 ns	11.92 ns	8.94 ns	7.15 ns	5.48 ns
NOR	2.84 ns	2.81 ns	2.96 ns	3.01 ns	2.7 ns
EX-OR	29.43 ns	25.32 ns	16.41 ns	12.54 ns	3.57 ns
EX-NOR	30.2 ns	26.27 ns	16.85 ns	13.01 ns	3.83 ns
AND	36.13 ns	34.6 ns	34.3 ns	33.86 ns	33.37 ns
OR	63.9 ns	59.45 ns	57.18 ns	55.9 ns	55.31 ns

Table 4 reports the results for simulated logic gates and the effect of thermal analysis on total power dissipation. In Table 5, the effect of thermal analysis on propagation delay is summarized from logic gates simulation. For all logic gates, the total power dissipation increases with the increase in temperature while the propagation delay decreases. From the above analysis, the relation of the temperature on propagation delay and power dissipation is also plotted for all logic gates.

The nominal value of propagation delay and total power dissipation is considered at room temperature ($T = 300$ K), as shown in Fig. 7. Also, thermal stability is observed by finding the change in parameter for change in temperature. It is analyzed that for NOT gate; the total power dissipation changes $3.75 \text{ pW}/^\circ\text{C}$ and propagation delay changes $3.84 \text{ ps}/^\circ\text{C}$. Similar calculations are made for all logic gates. For the NAND gate, the total power dissipation changes $1.55 \text{ pW}/^\circ\text{C}$, and propagation delay changes $20.73 \text{ ps}/^\circ\text{C}$. For NOR gate, the total power dissipation changes $8.18 \text{ pW}/^\circ\text{C}$, and propagation delay changes $0.6 \text{ ps}/^\circ\text{C}$. For EX-OR gate, the total power dissipation changes $43.4 \text{ pW}/^\circ\text{C}$, and prop-

Fig. 7: Thermal analysis of logic (a) NOT (b) NAND (c) NOR (d) EX-OR (e) EX-NOR (f) AND (g) OR gates

agation delay changes 75.84 ps/°C. For EX-NOR gate, the total power dissipation changes 12.38 pW/°C, and propagation delay changes 76.90 ps/°C. For AND gate, the total power dissipation changes 10.88 pW/°C, and propagation delay changes 11.04 ps/°C. For OR gate, the total power dissipation changes 10.05 pW/°C, and propagation delay changes 5.49 ps/°C. These values support the excellent thermal stability of novel hybrid SETMOS logic gates.

5 Conclusion

The proposed SG-SET and hybrid SETMOS techniques are effective in ultra-low-power consumption, area, and scalability. The room temperature operation, CMOS bias, and CMOS process compatibility are the advantages of the hybrid SETMOS technique. Using this architecture, we have explored and investigated logic inverter, NAND, NOR, AND, OR, EX-OR, and EX-NOR gates. The functionality of logic gates is verified using transient analysis. All logic gates are also simulated using 22-nm CMOS technology using the same simulation environment. We observed more than 90 % less power consumption by hybrid SETMOS logic gates than CMOS logic gates. Also, the proposed technique is found better compared to other hybridized techniques at the same bias. The thermal analysis has also been performed for all logic gates for 77 K, 150 K, 300 K, 400 K, and 500 K temperatures. We found the change in power dissipation for all logic gates is in the range of pW/°C, and the change in propagation delay is in the range of ps/°C. The obtained results reveal the robustness of our circuits against temperature variation. Hence, we analyzed that the logic gates can be further implemented in ultra-low power applications.

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Author Contributions

Design, Methodology, Formal analysis, and investigation, Validation, Writing - original draft preparation: [Raj Shah]; Conceptualization, Resources, Supervision: [Rutu Parekh and Rasika Dhavse]

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Not Applicable.

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