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Original Article

Designing, Simulation, and Performance-based Screening for a Power-Efficient Operational Transconductance Amplifier (OTA) Utilizing CNTFET Technology at a 22nm Node for Biomedical Applications

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Abstract *- Extremely low-frequency variations are often associated with physiological signals. Therefore, while acquiring physiological signals of human origin, the signal acquisition system interferes with several artefacts and noises. Thus, acquiring noise-free physiological signals of human origin using miniaturized, low-power external or implantable measurement devices is paramount for diagnostic and therapeutic purposes. The OTA serves as a basic component in analog signal-processing circuits, making it ideal for low-frequency electronic signal processing. Pure CNTFET, CNTFET-MOSFET hybridized, and MOSFET-based OTA-C circuits suitable for processing biomedical signals were designed at a 22 nm technology node and simulated to assess their performance using HSPICE. The design parameters included a Carbon Nanotube (CNT) diameter of 1.5 nm (with a chirality of (19, 0), a total of 10 CNTs/CNTFETs, and a pitch of 20 nm. The circuit was designed using a channel length of 22 nm and a channel width of MOSFET 381.5 nm. Following a curious analysis of the performance parameters, pure CNTFET-based OTA-C was screened as the most appropriate model for biomedical applications among all the four proposed OTA-C models as it exhibited high gain (38 dB), high phase margin (90.7◦), high unit gain frequency (19 MHz), and low power consumption (29 μW). The proposed pure CNTFET-based OTA-C was a high-gain-low-power-consuming stable building block (amplifier) appropriate for generating various diagnostic and therapeutic biomedical devices.*

Keywords *- HSPICE, CNTFET, OTA, Biomedical, Nano-electronics, DC gain, Bandwidth.*

1. Introduction

The most significant characteristic of the physiological signals of humans is that they operate at low Voltage and frequency ranges [1]. Physiological bio signals picked up by transducers and bio electrodes remain contaminated with baseline wander (movement/ respiration-dependent low-frequency artefacts), noise, artefacts, and drift (electronic process-dependent low-frequency artefacts) [2]. A range of frequencies constitutes a physiological signal that could be measured and analyzed as a first harmonic (Fundamental frequency) and harmonics (multiples of the first harmonic). The amplitude of the biosignal decreases with the increase in frequency until it is lost in the noise, suggesting the development of signal processing systems such as amplifiers and filters (low-pass or high-pass filters) that can ideally amplify and process actual bio signal while removing all other electrical contaminants; thus, the bio-signals being weak in characteristics requires their Amplification [2, 3]. The rising demand for portable and miniaturised devices stems from the necessity of detecting weak physiological and other biomedical signals that could be easily interfered with by thermal or flicker noises and power-line distortion [4, 5]. One of the significant challenges of the biosignal acquisition device is high power dissipation; therefore, the rapid development of the power-efficient analogue-circuit scheme has recently occurred. While designing a practical electronic circuit for picking up the physiological signals, parameters such as power consumption, high gain, phase margin improvement, and miniaturization (size reduction) should be emphasized [6-8]. OTA has been recognized as one of the key blocks for processing analogue biomedical signals [9, 10]. Because of its on-chip tuning potential, OTA behaves as a versatile, strong building block [11]. OTA belongs to a family of devices where the input voltage regulates the output-current source. The difference between two voltages represents the input signal, while the output current is determined by the variation between these voltages. An additional input terminal is supplied for a current to modify the amplifier's transconductance. The OTA is symbolized in Figure 1 [12, 13]. The relation of the transconductance (gm) of OTA with the output current (I_O), bias current (I_b), and volt equivalent temperature (V_T), varying current at the output terminal of OTA, is illustrated in Figure 1. The value of V_T of OTA is 26 mV when measured at room temperature. Bias current (I_b) maintains the linearity of the transconductance (gm) over a wide range. The effectiveness of portable devices is associated with battery life. The number of transistors/chips has swiftly increased with the miniaturization of the transistors. Short Channel Effects (SCEs) playing a critical role in power consumption during remains turned off has been documented as one of the significant challenges of CMOS technology beyond 22 nm.

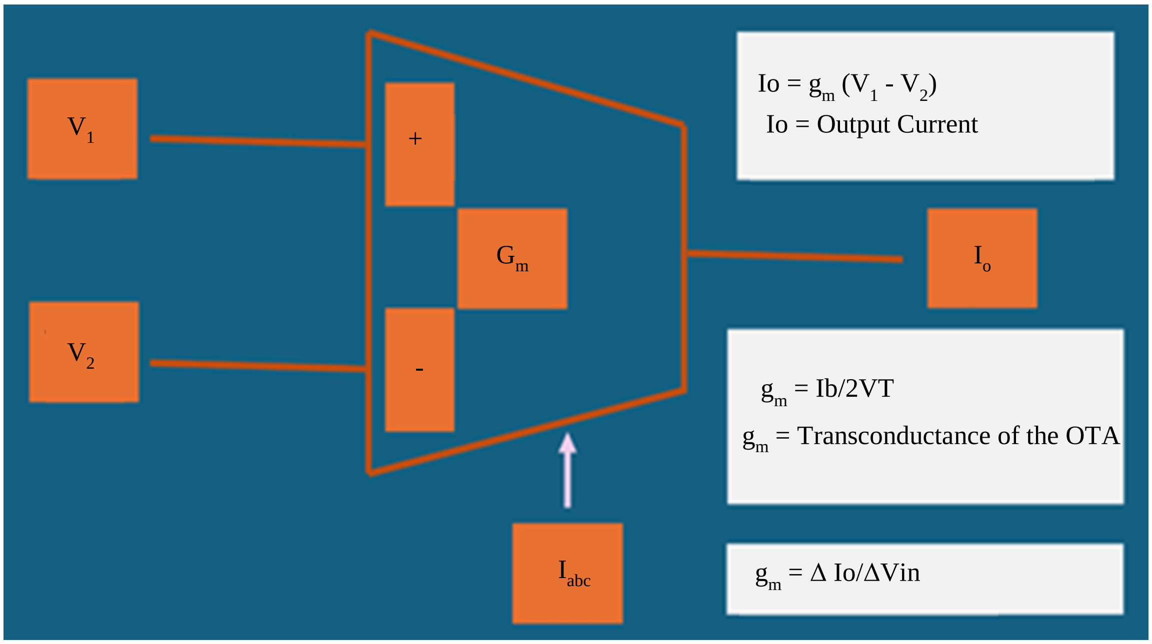

Fig. 1 Depiction of the ideal model of the OTA, Ib = Bias current of OTA, VT = Voltage equivalent temperature, and ($V_1 – V_2$) = differential voltage, ΔI_O = varying current, and ΔV_{in} = varying voltage at the output terminal

Fin-Shaped FETs, Tunnel FETs, and CNTFETs have surfaced as technological advancement to overcome the SCEs issues [14]. In the current environment, the fast-increasing semiconductor industry has reduced the channel length of MOSFETs to ever-smaller dimensions ranging from a few micrometres to less than 14nm. Consequently, the contribution of the Si-based MOSFETs as performance enhancers in digital applications will no longer be relevant [15]. Moreover, reducing power consumption while retaining precision is a desirable trait for biomedical devices, and that could be achieved by designing a power-efficient CNTFET-OTA-C using CNTs due to its astounding properties [16].

An active device such as CNTFET-OTA-C could be used to design a device like a notch filter to suppress the biological signal noise of a specific frequency range [13, 17]. Thus, the role of the CNTFET-OTA-C could be remarkable in Power-Line Inference (PLI) suppression during ECG recording to maintain the quality of the ECG signal [18]. While there have been some studies examining the performance of CNTFET-based and CMOS-based OTAs at technology nodes of 32nm, 45nm, and 95nm, a comprehensive comparative analysis specifically focused on CNTFET-based, CMOS-based, and hybrid OTAs at the 22nm technology node is still lacking. This represents a notable research gap. Consequently, this research aims to design, simulate, and evaluate the performance of a power-efficient CNTFET-based Operational Transconductance Amplifier (OTA) for biomedical applications at the 22nm technology node. This work seeks to enhance the comprehension of the strengths and drawbacks of CNTFET-based OTAs in comparison to their CMOS counterparts. Moreover, optimizing channel width, length, and CNT specifications in CNTFET-based OTA design is essential for achieving high performance, power efficiency, and signal integrity at the 22 nm technology node.

Proper channel dimension selection is crucial in maintaining an optimal balance between transconductance, leakage currents, and switching characteristics, ensuring reliable functionality in biomedical applications. Moreover, key CNT attributes such as diameter, chirality, and density significantly impact threshold voltage, carrier mobility, and overall transistor behavior. Ensuring precise regulation of these parameters enhances scalability, power efficiency, and noise reduction, vital for wearable and implantable medical devices. A systematic evaluation framework is employed to refine these design choices, enabling an optimized architecture suited for biomedical electronics. Furthermore, The CNT diameter influences bandgap, threshold voltage, and carrier mobility, impacting transconductance and leakage currents. Pitch, or CNT spacing, affects density, current drive, and parasitic capacitance, where higher density improves performance but may introduce screening effects. Optimizing these parameters enhances power efficiency, gain, and noise performance in CNTFET-based OTAs.

2. Comparison of the Existing Technology with CNTFET and Limitations

Conventional MOSFET-based OTAs encounter significant challenges, particularly at advanced technology nodes, due to SCEs, elevated leakage currents, and reduced carrier mobility, which degrade overall performance. Their inherent high-power consumption, limited gain, and increased noise levels further restrict their effectiveness in power-efficient implantable medical devices. The scaling of MOSFET devices into the nanoscale regime increases their sensitivity to variations in process parameters, which results in performance degradation due to Short-Channel Effects (SCEs) like Drain Induced Barrier Lowering (DIBL), velocity saturation, and impact ionization. Hajare et al. demonstrated performance improvements with Fin-FET and CNTFET technologies at the 14nm node, revealing that both exhibit superior performance and scalability. Nonetheless, Fin-FETs also experience performance limitations beyond the 14nm technology node, negatively impacting integrated circuit performance. In contrast, CNTFETs have been identified to be offering enhanced performance relative to Fin-FETs. They are proposed as a promising alternative for applications beyond 14nm, potentially benefiting the silicon industry for low-power and high-performance integrated circuits [19]. Numerous foundries are investigating various nanoscale devices to achieve optimal circuit performance metrics, including graphene FETs, nanowire FETs, and Tunnel-FETs (TFETs) [20, 21], alongside CNTFETs [14, 22] and multi-gate transistors like Fin-FETs [23]. Among these, CNTFETs are considered the most promising option [24], attributed to their ultrathin body from the smaller diameter, exceptional carrier mobility, low OFF-current, aggressive channel length scaling, ballistic conduction, and semiconducting properties [25, 26]. Additionally, previous design methodologies often rely on empirical optimization techniques, lacking a systematic and comparative performance evaluation framework, which can result in suboptimal circuit efficiency. These limitations underscore the need for alternative device architectures like CNTFETs, which exhibit enhanced scalability, superior power efficiency, and improved noise characteristics. By addressing the challenges of existing technology and overcoming its limitations, CNTFETs are more suitable components for next-generation biomedical electronics.

2.1. A Brief Review of Carbon-Nanotube Field-Effect Transistor (CNTFET)

CNT with a high aspect ratio possesses remarkable conduction properties (both thermal and electrical); therefore, its wide range of applications in developing Nano electronics, Nano-biosensors, field-emission-based displaying units, and nanocomposite materials are underlined [27].

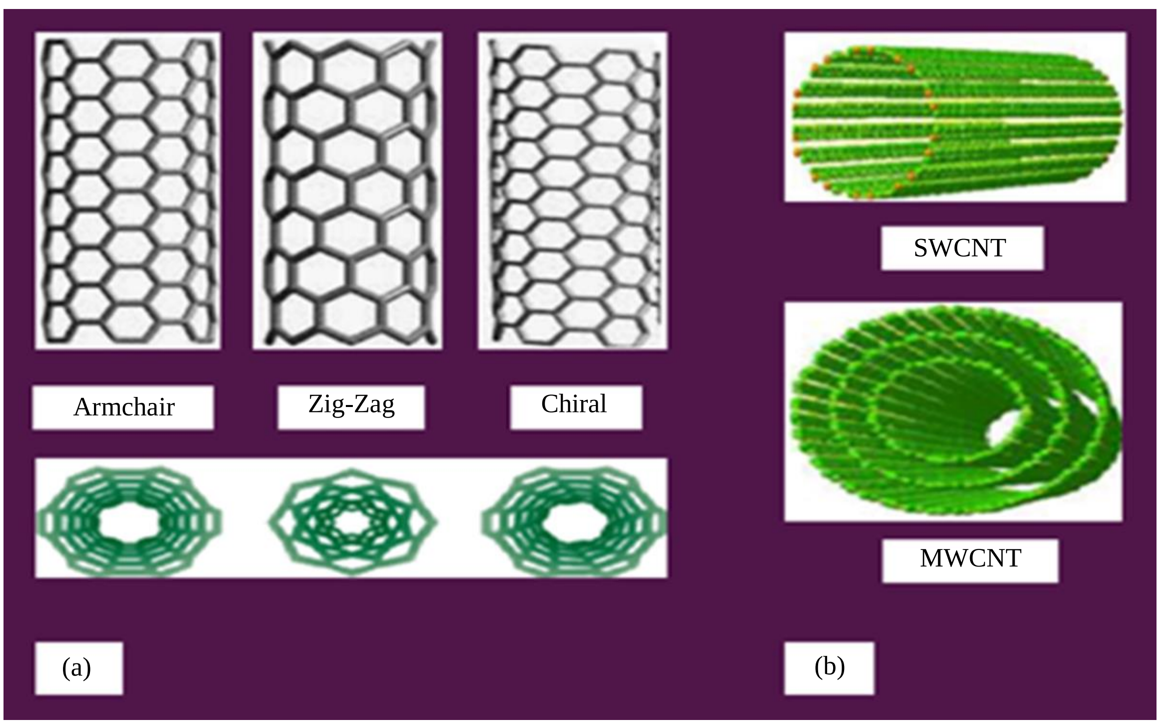

Fig. 2 Forms and configurations of the CNT (a)-different forms of the CNT, and (b)-different configurations of the CNT.

The two types of CNTs are Single-Wall (SW) CNTs and multi-wall CNTs, differentiated by the number of carbon nanotubes involved. Chiral features and configurations of the CNTs are represented in Figure 2 [28]. Due to the various distinguishing characteristics of CNT, like mobility and conductivity, upgraded CNT-based transistors exhibited remarkable potential to impact the future of CMOS technology. The CNT-FET is advantageous over CMOS-FET because of its unidimensional ballistic transport, excellent carrier mobility, and high drive current with minimal power consumption while maintaining precision [29].

Most research is focused on the performance of pure CNTFET technology in various analogue circuits and miniaturized-system applications. The combinations of NMOS and PMOS transistors constitute the conventional CMOS. However, in a hybrid CMOS-CNTFET such as NCNTFET-PMOS-circuitry, the sink and source pair are NCNTFETs and traditional PMOS transistors. In the same way, PCNTFET-NMOS hybrid circuitry, source, and sink pair are conventional NMOS transistors and the PCNTFET [30]. Diverse combinations of the NMOS and PMOS with integrated CNTFET as analogue circuit designing tools could be harnessed to achieve power-efficient CNTFET circuits for various applications, particularly biomedical applications.

3. Research Methodology

The Hspice simulation tool was used to execute the four proposed OTA-C simulations, and the proposed configuration of OTA-C and simulation parameters are described below;

3.1. Configuration of Proposed OTA-C

In the present study, three different designing configurations of OTAs were undertaken: pure CNT-OTA (all the transistors incorporated were designed using CNTS) (Figure 3(c)), hybrid PCNTFET-NMOS-OTA-C (PCNT-based transistors as source and NMOS-transistors as sink in designing consideration) (Figure 4(c)), and NCNTFET-NMOS-OTA-C (PMOS transistors as source and NCNTFE-based-transistors as sink in designing consideration) (Figure 5(c)). A conventional CMOS-based OTA-C was also designed and studied to gain comparative insight into the performance parameters (Figure 6(c)).

3.2. Simulation Criteria of Proposed OTAs

The four configurations of new types of OTA-Cs were designed at the 22 nm technology node, and simulation was executed using HSPICE. The OTA-C circuits using CNTFET were designed by considering the Channel Length = 22 nm, chirality (19, 0), with number of CNT-tubes/transistor = 10. For comparative analysis, a CMOS-based OTA-C was simulated by HSPICE by considering the Channel Length of 22 nm with a channel width of 381.5 nm. For simulating the OTA-Cs, capacitive load (CL=1pf), supply voltage 0.9V, pitch (S) of 20 nm, with CNT diameter (DCNT) of 1.5 nm.

4. Simulation Results and Discussion

High-performance next-generation nano-electronic circuits based on CNT with a unique combination of geometric and electronic characteristics have evolved remarkably in the recent past [31]. Realizing a high-gain-low-power system poses an exceptional challenge because of the contradictory requirements for achieving the While systems typically aim for low power consumption and high gain, the increasing demand for portable equipment in biomedical applications has intensified the need for circuit designs that effectively balance low-power with high gain [32]. High gain is needed for low-voltage applications to achieve high accuracy [32]. Various modelling methods for enhancing the DC gain have been reported, for instance, cascading multiple (two or more stages) stages and increasing output impedance; however, cascading leads to stability issues, whereas enhancing the DC gain.

Furthermore, implementing cascading gain-boosting enhances output impedance but increases voltage headroom consumption, rendering it inappropriate for low-voltage applications [33]. Efforts are required at the level of designing a building block to compensate and resolve the issue [34]. Consequently, there is a critical need for amplifiers that deliver high gain while maintaining low power consumption, particularly for applications in the biomedical field. Therefore, the current research attempted to achieve high-gain and low-power architecture. Three CNTFET-based and one MOSFET-based OTA-C models were comprehensively studied to gain a suitable performance spectrum for biomedical applications. Comparative DC gain analysis unveiled that the PURE CNTFET-OTA model yielded a maximum gain of 38 dB compared to the other three models (Table 1).

The gain achieved with the PURE CNTFET-OTA-C model was approximately 6 times higher than that of the PURE CMOS-OTA-C (gain = 6.3 dB), as illustrated in Figures 3(a) and 6(a). The gain obtained by two hybrid models, NCNTFET PMOS-OTA-C (gain = 12.8 dB, Figure 5(a)) and PCNTFET NMOS-C (gain = 13.8 dB, Figure 5(a)), were comparable to each other but higher than that of PURE CMOS-OTA-C. To our knowledge, at the 32 nm technology node, CNTFET-based OTA has been reported; however, the CNTFET-based OTA-C has not been reported at 22 nm technology node. Comparison of performance of the CNTFET-based and CMOS-based-OTA at different technology node has been tabulated (Table 2). The finding suggests that applying CNTs in the circuit increased the gain significantly, probably attributable to the elevated conductance levels and substantial driving force associated with one-dimensional ballistic transport. Current research showed that the CNTFET-based OTA design achieved a higher gain than MOSFET-based OTAs. The improvement is attributed to CNTFETs' higher carrier mobility and superior electrostatic control, which leads to better transconductance and lower short-channel effects.

Table 1. Comparison of performance metrics of CNTFET, hybrid OTA at capacitive load (CL)=1pf, Vdd = 0.9V, with N=10, S=20 nm, DCNT=1.5nm and pure CMOS OTA at technology node = 22 nanometer

Parameters	PURE CNTFET-based-OTA	NCNTFET PMOS-based OTA	PCNTFET NMOS-based OTA	PURE CMOS-based OTA
DC Gain (dB)	38	12.8	13.8	6.3
Bandwidth	0.27 MHZ	2.7 MHZ	81.4 KHZ	86 KHZ
RO (KΩ)	7.4	11.4	381	764
Average Power	29uW	23.4uW	431.3nW	193nW
Phase Margin in Degree	90.7	103	101	118.9
Gain Margin	-37	-11.8	-12.9	-5.4
UGF (MHZ)	19	10.3	0.35	0.135
Gain Max	37	11.8	12.9	5.4
fmax	100	125.8	15.8	3.98

Table 2. A comparative analysis of the performance characteristics of the proposed OTA in relation to previously reported OTAs

References	[22]	[35]	[36]	[37]	[37]	Proposed Work	
Technology	32 nm	45 nm	65 nm	65 nm	65 nm	22 nm	22 nm
	CNTFET	MOSFET	MOSFET	MOSFET	MOSFET	MOSFET	CNTFET
DC gain (dB)	21.34	66.5	75.3	46	43	6.3	38
Supply volt (V)	0.9	1	1	0.50	0.35	0.9	0.9
Average Power	8.25 μW	68 μW	129 μW	182 μW	17 μW	193 μW	29 μW
Load CL (pF)	5	10	10	3	3	1	1
Phase margin◦	85	61	138	57	56	90.7	118.9
Bandwidth (MHz)	9.5	-	-	38	3.6	0.086	0.27

The higher gain ensures precise signal amplification, making it particularly advantageous for biomedical signal acquisition systems, such as ECG, EEG, and neural recording applications, where weaker biosignals require accurate processing [16]. High gain has also been reported by Loan et al. in CNT-based OTA-C at the 45 nm technology node; however, our result is at the 22 nm technology node [38]. A similar finding (high gain in CNT-based circuit compared to CMOS) was observed in another comparative analysis of the CNT-based circuit simulated at 32 nm node. Another comparative analysis showed that the CNT-based OTA-C designed at 32 nm technology exhibited a high gain (18.5 dB) compared to pure MOS [39].

A gain of 38 dB achieved in the currently proposed OTA-C model by simulating PURE CNTFET-OTA-C at a 22 nm technology node reflected a promising result for biomedical applications. Energy delivery, conversion (analogue-to-digital), processing of signals, and communication sub-systems are the key components of biomedical devices, and each of these significant components necessitates the designing architecture, which must consume minimum energy for its applicability in biomedicine [40]. Therefore, circuit design with low power consumption (ranging from microwatts to nanowatts) is recommended for biomedical applications [40]. Low power consumption enhances the battery life in biomedical devices, especially implantable [41] and wearable devices [42]. This research attempts to tackle the challenge of achieving low-power consumption by employing the simulation and comparing CNT-based OTA-Cs. Low power consumption (29 uW) was achieved in the PURE CNTFET-OTA-C with appropriate DC gain for biomedical applications (Table 1, Figure 3(b)). Slightly lower power consumption was recorded in two hybrid models and PURE MOSFET-based OTA-Cs; however, the DC gain yield was significantly low in these three models compared to PURE CNTFET-based OTA-C (Table 1, Figure 4(b), 5(b), and 6(b)). Our findings indicate that the PURE CNTFET-based OTA-C demonstrates high gain and low power efficiency, rendering it well-suited for biomedical applications [43], such as implantable, wearable, and point-of-care portable diagnostic devices [44, 45]. The current research findings suggest that CNTFET-based OTAs offer superior energy efficiency compared to MOSFET-based OTAs, making them highly suitable for implantable and energy-constrained biomedical applications [46]. Their capability to function at lower supply voltages (less than 1V) substantially diminishes power dissipation. This ultra-low power consumption is crucial for implantable devices such as pacemakers and neural stimulators, where extended battery life minimizes surgical risks and maintenance costs [46]. Additionally, CNTFET-based OTAs generate less heat, preventing thermal damage to biological tissues and ensuring safe and long-term operation in medical implants [47]. Their low power requirements also enhance compatibility with energy-harvesting technologies, enabling self-powered biomedical devices that eliminate reliance on frequent battery replacements, unlike MOSFET-based OTAs with higher energy demands [48]. Another key performance parameter is phase margin, which typically indicates the system stability, including OTA.

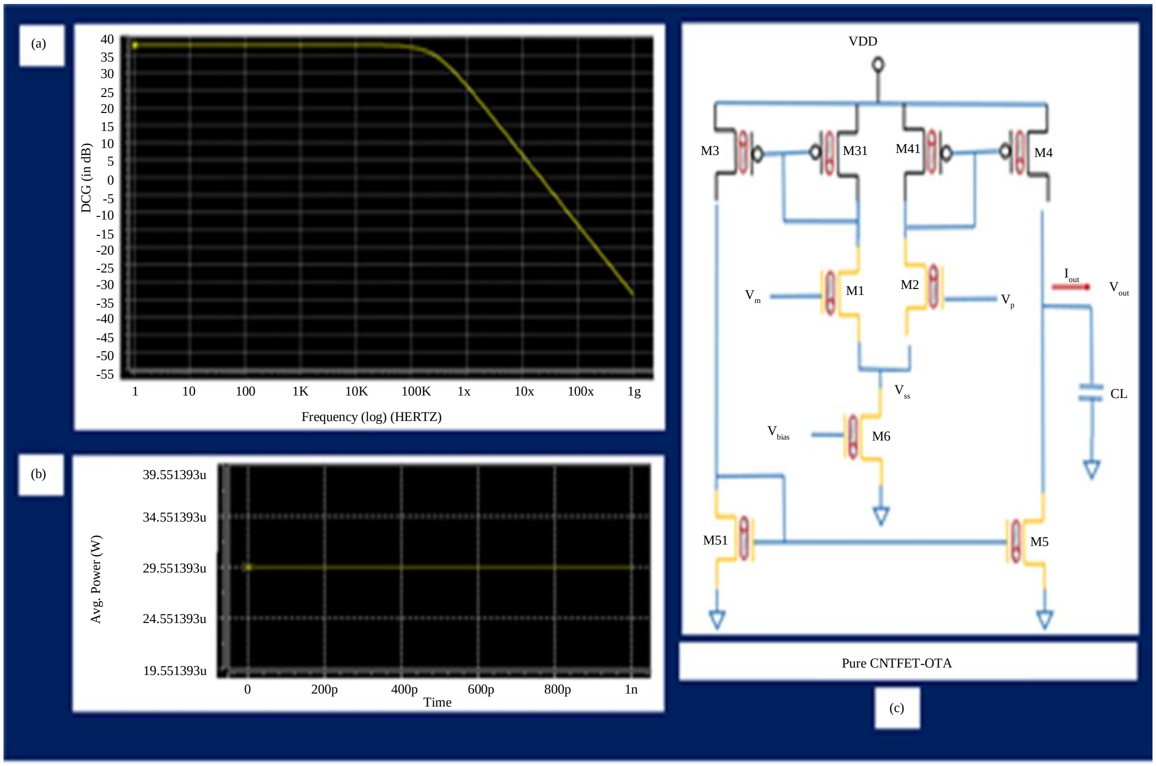

Fig. 3 Performance parameter of pure CNTFET-OTA-C (a) Depicts DC gain graph, (b) Average power consumption, and (c) Depiction of the topology of the hybrid PCNTFET-OTA-C VDD=0.9V, C_L = 1pf, Channel Length (L) = 22nm, Number of CNTS (N) = 10, CNT-Pitch(S) = 20nm, CNT-Diameter (D_{CNT}) = 1.5nm, dB = decibel, Avg = Average.

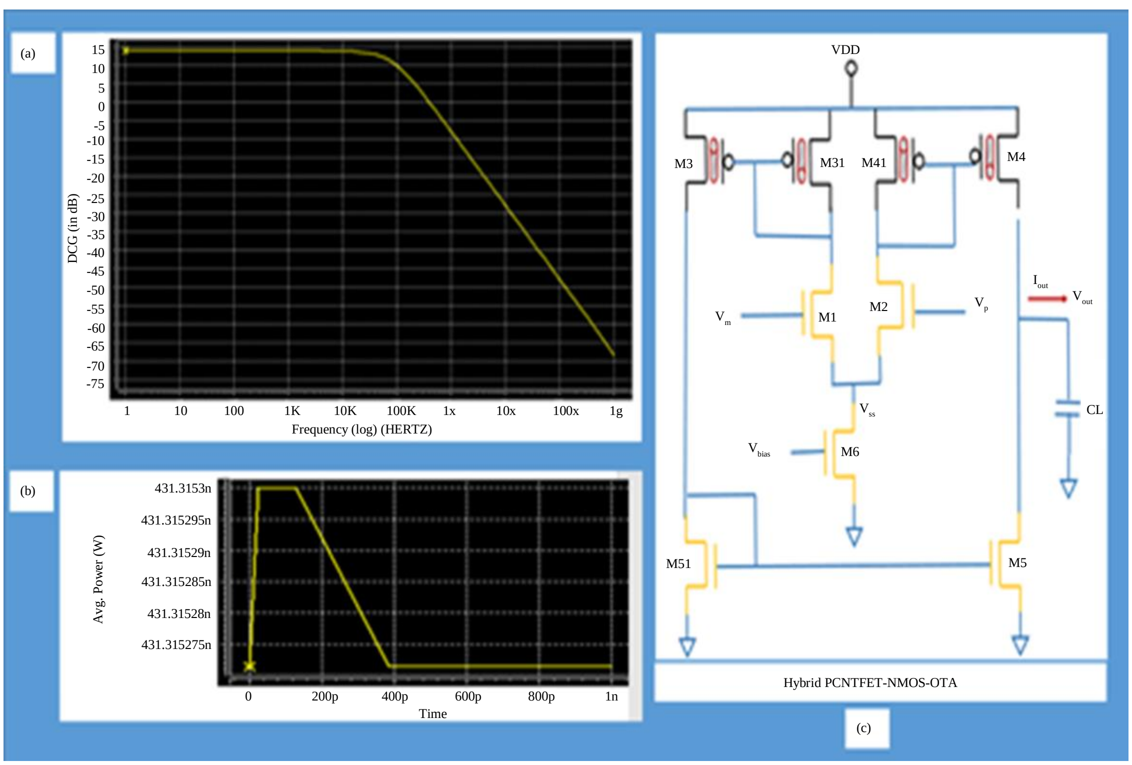

Fig. 4 Performance parameter of PCNTFET-NMOS-OTA-C (a) Depicts DC gain graph, (b) Average power consumption achieved on simulation, and (c) Depiction of topology of the hybrid PCNTFET-OTA-C, VDD=0.9V, CL = 1pf, Channel Length (L)= 22 nm, Number of CNTS (N) = 10, CNT-Pitch(S) = 20 nm, CNT-Diameter (DCNT) = 1.5 nm, dB = decibel, Avg = Average.

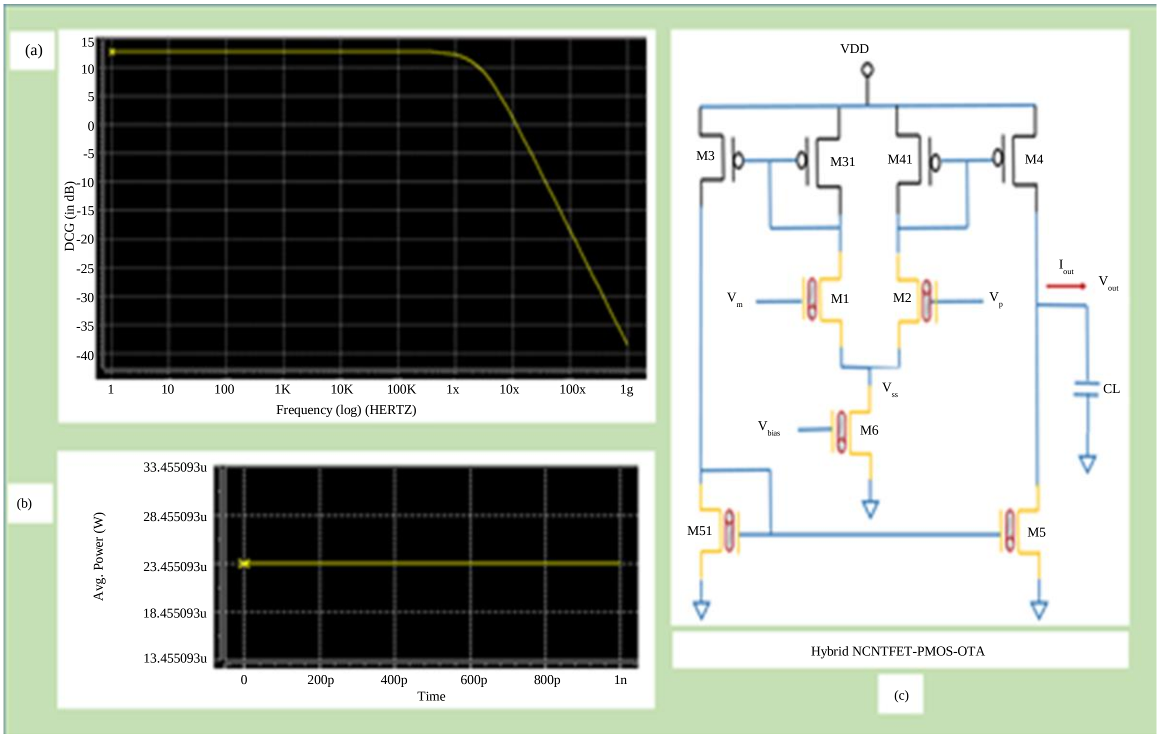

Fig. 5 Performance parameters of the hybrid-NCNTFET-PMOS-OTA-C (a) Representation of the DC gain achieved on simulation, (b) Average power consumption achieved on simulation, and (c) Depiction of the topology of the hybrid NCNTFET-OTA-C. VDD=0.9V, CL = 1pf, Channel Length (L) = 22 nm, Number of CNTS (N)=10, CNT-Pitch(S)= 20 nm, CNT-Diameter (DCNT) = 1.5 nm, dB = decibel, Avg = Average.

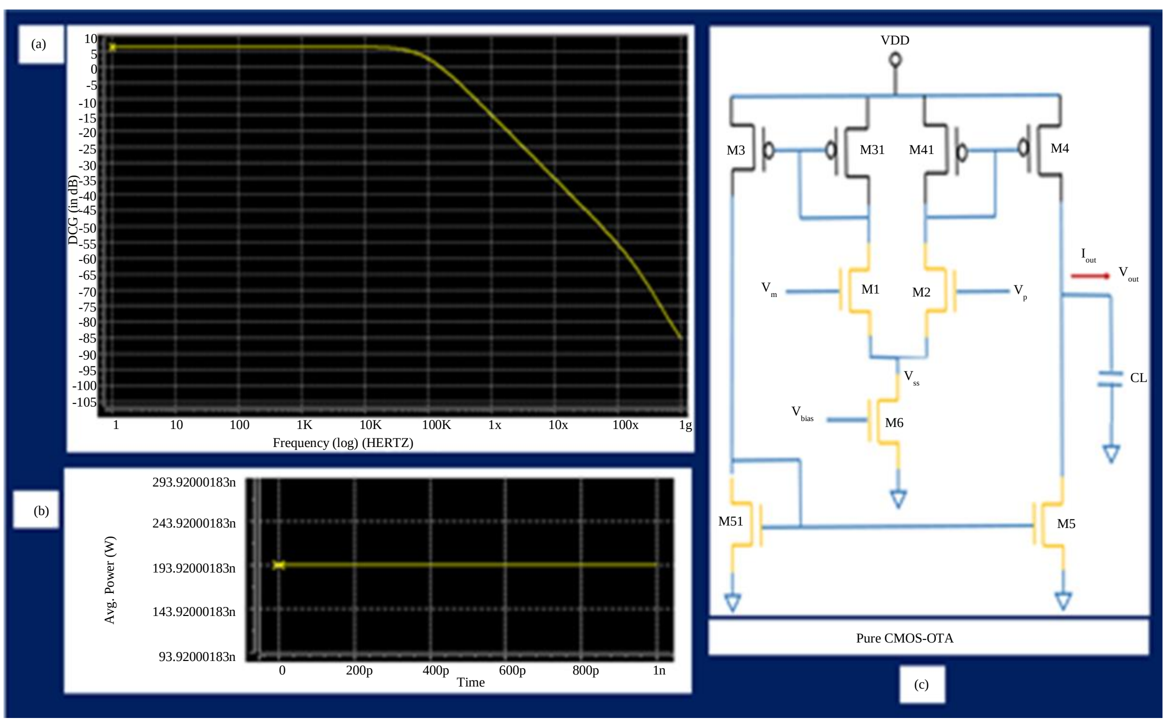

Fig. 6 Performance parameter of pure CMOS-OTA-C circuit (a) DC gain achieved on simulation, and (b) Shows the graph of average power consumption achieved on simulation, and (c) Depiction of the topology of the CMOS-OTA-C. VDD = 0.9V, CL = 1pf, Channel Length (L) = 22 nm, and Avg = Average.

Phase margin represents the additional phase lag necessary to drive the system to the instability threshold. A low phase margin means the OTA is close to instability, and minor variations can lead to undesirable behaviours, such as oscillations or excessive overshoots in the output signal. Meanwhile, the high phase margin (usually >45-60 degrees) implies a more stable response to input signals, which typically means that the OTA will exhibit less oscillation and ringing, even when subjected to load changes or temperature variations [49]. Thus, a high phase margin generally correlates with better stability, ensuring that the OTA performs reliably over time and under varying conditions [50, 51]. Stability analysis showed that the PURE CNTFET-based OTA-C was a high-gain, low-power stable model with a higher phase margin 90.7 (Table 1). Regarding stability, the other three models (PURE-CMOS-based,119; PCNTFET-based, 101; and NCNTFET-based OTA-Cs, 103) showed higher stability; however, the gain was low (Table 1). Our finding corroborates with a finding of stability analysis of OTA reported by Shah et al. [52]. This research demonstrated that CNTFET-based OTAs achieved a greater phase margin than MOSFET-based OTAs, ensuring greater stability and noise immunity in biomedical applications [53].

Therefore, the superior electrostatic control and reduced short-channel effects minimize phase variations, preventing instability in ECG, EEG, and biosensor circuits. This enhanced stability reduces oscillations and signal distortion, making proposed CNTFET-based OTAs ideal for reliable, long-term biomedical monitoring in wearable and implantable devices. To facilitate screening, an evaluation of the unit gain frequency - one of the critical performance parameters of OTAs - was conducted for all four OTAs, followed by a comparative analysis. A high Unit Gain Frequency (UGF) or gain-bandwidth product of OTA implies a faster response of the system to changes in an input signal, which infers that the OTA can maintain functional performance over a broader frequency range [54]. It also implies that the OTA can be used in high-frequency circuits like filters, oscillators, and communication systems without significant degradation in performance due to bandwidth limitations [54].

However, it is challenging to have a high unit gain frequency, high phase margin, and low power consumption simultaneously because a high unit gain frequency often comes with trade-offs such as consumption of more power and reduction in phase margin, leading to the stability problem (for instance, oscillation) if the circuit is not designed correctly. In summary, a high unit gain frequency infers that the OTA can operate at higher frequencies and maintain a good level of performance; however, careful balancing is required to ensure stability and power efficiency. The Unit gain frequency of PURE CNTFET-based OTA-C was recorded as 19 MHZ, higher than that of the other three proposed models under study (Table 1). In a study, a novel architecture with suitable performance OTA was reported with a UGF of 141KHZ [54]. Keeping all the critical performance parameters of all the proposed models in view, the PURE CNTFET-based OTA-C model could be screened as the most suitable model for biomedical applications. However, this research has limitations of a negative gain margin coupled with a high phase margin. Though the system PURE CNTFET-based OTA-C model showed a high phase margin (90.7), the gain margin is -37, indicating that the system has a stable phase behaviour but an insufficient gain margin. This means that although the phase response is favourable, the system's gain is already too high, or it is too close to the critical point where the open-loop gain reaches 1 (0 dB) at the frequency where the phase is -180°, suggests that the system might already be oscillating or close to instability, and reducing the system gain could stabilize it.

The novel aspect of this study resides in the incorporation of Carbon Nanotube Field-Effect Transistors (CNTFETs) within an Operational Transconductance Amplifier (OTA) at the 22 nm technology node, representing a substantial advancement over conventional MOSFET-based architectures. Unlike conventional approaches, this study focuses on optimizing the OTA for biomedical applications, where ultra-low power consumption, high gain, and minimal noise are critical for implantable and wearable medical devices. A key innovation is the implementation of a performance-based screening methodology, which systematically evaluates essential parameters such as bandwidth, power efficiency, linearity, and noise performance, ensuring an optimized design. The proposed CNTFET-based OTA demonstrates superior power efficiency and miniaturization, making it highly suitable for next-generation compact biomedical devices. This work highlights CNTFET technology's advantages in enhancing gain and improving energy efficiency through a detailed comparative analysis with MOSFET-based OTAs.

Although CNTFETs hold significant potential for applications in medical devices such as wearable technologies, sensors, and diagnostic tools, it is essential to conduct a thorough risk assessment and long-term safety evaluation of Carbon Nanotubes (CNTs) before their use in biomedicine. This includes a comprehensive toxicological assessment of the CNT material. Furthermore, a more profound understanding of how physiological mechanisms interact with CNT administration in the human body is crucial. The advancement in the application of carbon nanotubes in biomedicine can only be suitable once safety issues, particularly regarding the toxicity of CNTs, are adequately addressed.

5. Application and Future Perspective

The proposed CNTFET OTA demonstrates impressive performance characteristics, including low power consumption (29 µW), high gain (38 dB), substantial phase margin (90.7°), and a high unit gain frequency (19), all achieved with a low power supply voltage. Consequently, this CNTFET design has the potential to significantly impact the biomedical sector, particularly in applications such as sensors, notch filters, and bandpass filters. Stabilizing the PURE CNTFET-based OTA-C model by increasing the gain margin along with phase margin while maintaining high gain, which could be achieved by causing variations in CNTs number and chirality of the CNTs and experimental validation of the simulation results will be the future direction for this research. Moreover, future research will also include creating various diagnostic and therapeutic biomedical devices using the proposed pure CNTFET-based OTA-C blocks.

6. Conclusion

The current research provides a deep insight into designing and simulating four different OTA-Cs circuits and screening a best-performing design architecture suitable and appropriate for biomedical applications. An H-spice-based simulation was executed for one pure CNTFET-based OTA-C, two CNTFET-MOSFET hybridized circuits, and one pure-MOSFET-based OTA-C at a 22 nm technology node. The performance parameters, especially high gain, high phase margin, High unit gain frequency, and low power consumption, were assessed to screen and determine the best model (high-gain-low-power consuming stable circuit model) appropriate for biomedical applications. The supply voltage, channel length, DCNT, number of CNTs/FET, and width for pure CMOS-based OTA-C were 0.9 V, 22 nm, 1.5 nm, 10, and 381.5 nm, respectively. Following a curious analysis of the performance parameters, it was observed that the pure CNTFET-based OTA-C was the most appropriate model for biomedical applications as it exhibited high gain (38 dB), high phase margin (90.7), high unit gain frequency (19), and low power consumption (29 uW). The pure CNTFET-based OTA-C could be a significant building block for generating analogue circuits. Moreover, it was noticed that the gain achieved with the application of the CNTFET compared to that of the MOSFET was approximately 6 times higher, suggesting the remarkable potential of CNTs to realize high gains with low-power-consuming building blocks. Although the model proposed in this research exhibited a high phase margin to explain the system stability, the negative gain margin reflects the limitation of the study.

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