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Original Article

Quantitative Impact Assessment of CNTs as the Channel Materials on the Performance of the Proposed Power-Efficient CNTFET-based Operational Transconductance Amplifier Capacitor (OTA-C) for Biomedical Suitability Across Various Technology Nodes

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Abstract - *Extremely low-frequency variations are commonly associated with physiological signals. As a result, the signal acquisition system is often affected by various artefacts and noises while acquiring human physiological signals. Therefore, obtaining noise-free physiological signals from the human body using miniaturised, low-power external or implantable devices is crucial for diagnostic and therapeutic applications. The OTA is a flexible component in analogue signal-processing circuits, ideal for low-frequency signal-processing applications. CNTFET-based OTA-C circuits designed for biomedical signal processing were proposed at three technology nodes (14 nm, 22 nm, and 45 nm) and simulated using HSPICE to evaluate their performance. Moreover, the impact of variations in the number of CNTs on performance parameters of the CNTFET-based OTA-Cs was assessed across the 14 nm, 22 nm, and 45 nm technology nodes. The simulation parameters for the CNTFET-based OTA-C were capacitive load/CL = 1 pF, supply voltage of 0.9V, and pitch (S = 20 nm) with varying numbers of CNTs. The maximum gains obtained at CNTs = 20 were 44.429 dB, 38.159 dB, and 25.289 dB at 14 nm, 22 nm, and 45 nm at the technology nodes, respectively. The average power consumption of the CNTFET-OTA-Cs at 14 nm, 22 nm, and 45 nm was recorded to be 13.47 µW, 59.09µW, and 68.56µW. The phase margins obtained at CNTs = 20 across technology nodes 14 nm, 22 nm, and 45 nm were 90.336 degrees, 90.697 degrees, and 93.111 degrees, respectively. Additionally, gain increases with an increase in the number of CNTs. However, it stabilised around tube numbers 16-20 across the three technology nodes. The phase margin decreased with the increase in the number of CNTs, which stabilised around tube numbers 15-20 only at technology nodes 14 nm and 22 nm, while at 45 nm, it remained fluctuating around tube numbers 15-20. The simulation results of the performance parameters for this proposed circuit indicated the potential of this OTA circuit as a crucial component for biomedical applications, including wearable and implantable miniature sensors.*

Keywords - *CNTs, CNTFET, HSPICE, OTA-C, Nanoelectronics.*

1. Introduction

Operational Transconductance Amplifiers (OTAs) integrated into nanoelectronics can be crucial in advancing biomedical applications, especially with the rapid growth of biomedical devices, sensors, and implantable electronics [1, 2]. OTAs are highly effective for efficiently amplifying and processing weak biological signals, making them ideal for applications like biosensors, health monitoring, medical diagnostics, and neuroprosthetics. OTA-based highly sensitive biosensors detect biomolecules, pathogens, or genetic material with high sensitivity, low power consumption, and real-time monitoring capabilities [3, 4]. Bio-signals, such as Electrocardiogram (ECG) [5], Electroencephalogram (EEG) [6], and Electromyogram (EMG), have distinct characteristics that make them crucial for health monitoring and medical diagnostics [5]. These signals are low amplitude (in millivolts) and complex (non-linear, reflecting the dynamic nature of the underlying physiological process) [6]. Additionally, bio-signals are extremely susceptible to noise from external (power lines, environmental factors) and internal sources (muscle movement) [7]. Significant individual variation in physiological signals reflects its personalised diagnostic potential, while the rhythmic and periodic nature of the physiological signals, especially ECG and EEG, aids in distinguishing the normal from abnormal conditions [8]. However, such signals fall within the low-frequency range, requiring specialised filtering techniques for accurate detection [7]. A physiological signal consists of a range of frequencies that can be measured and analysed as the fundamental frequency (first harmonic) and its harmonics (multiples of the fundamental). As the frequency increases, the amplitude of the biosignal diminishes until it is overwhelmed by noise, which highlights the need for signal processing systems, such as amplifiers and filters (low-pass or high-pass, band-stop filter, notch filter), which can amplify and process the true biosignal while eliminating electrical interference. Consequently, due to the weak nature of biosignals, amplification is essential [7, 9]. The increasing demand for portable and compact devices arises from the need to detect weak physiological and other biomedical signals, which are highly susceptible to interference from thermal or flicker noise [10, 11]. Another significant challenge in bio-signal acquisition devices is high power dissipation, which has led to the recent advancement of power-efficient analog circuit designs. Factors such as power supply, power consumption, high gain, phase margin enhancement, and miniaturisation (reducing size) should be prioritised when creating a practical electronic circuit for capturing physiological signals. [12-14]. The OTA is crucial for processing analog biomedical signals [15, 16]. Due to its ability for on-chip tuning, the OTA functions as a versatile and powerful building block [17]. The OTA is part of a group of devices in which the input voltage controls the output current source. The differential-voltage two points represent the input signal, while the output current depends on this voltage difference. An extra input terminal allows a current that adjusts the amplifier's transconductance. The OTA is symbolised as shown in Figure 1 [18, 19]. Figure 1 illustrates the relationship between the OTA's transconductance (gm), Output Current (I_O), Unit gain frequency, phase margin, Bias Current (Ib), Voltage equivalent temperature (VT), and the varying current at the OTA's output terminal. The VT value of the OTA is 26 mV when measured at room temperature. The transconductance gain (gm) remains linear over a wide range of bias current (Ib).

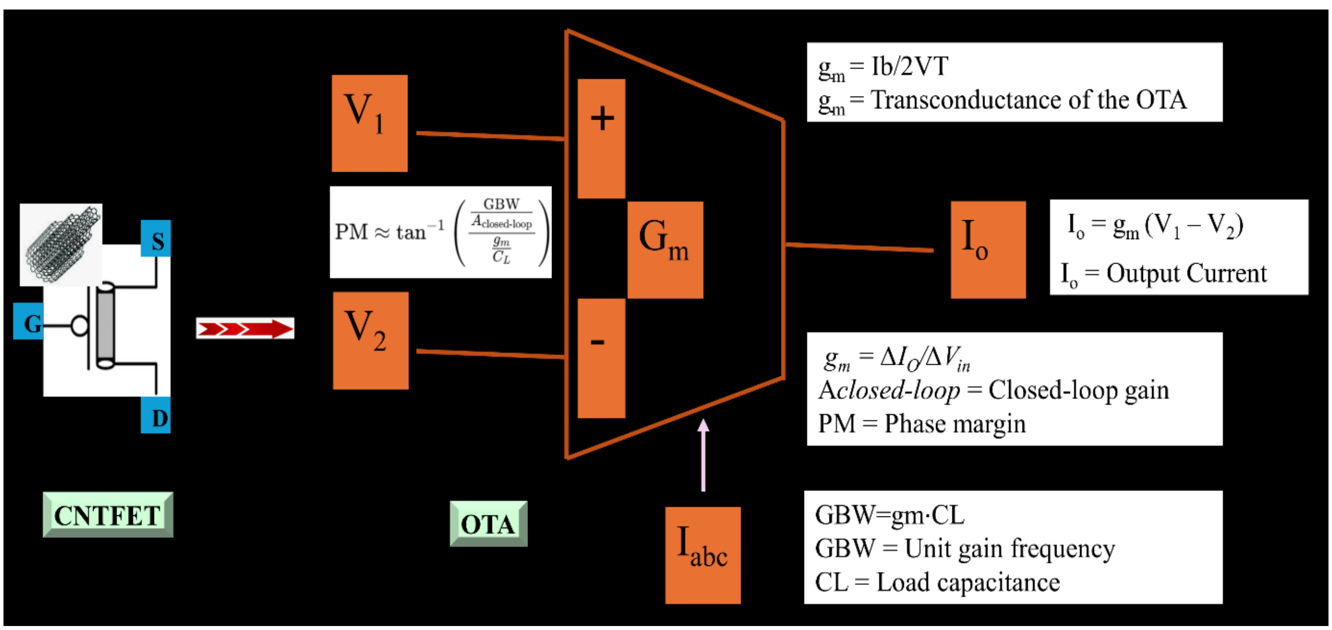

Fig. 1 Depiction of the ideal model of the OTA, Ib = Bias current of OTA, VT = Voltage equivalent temperature, and ($V_1 - V_2$) = differential Voltage. ΔI_O = varying current, and ΔV_{in} = varying Voltage at the output terminal

1.1. The Comprehensive Review of the Potential of the CNTs and CNTFETs-Based Electronic Devices

Carbon Nanotubes (CNTs) are cylindrical structures with remarkable electrical, mechanical, and thermal properties. These properties make them ideal for various electronics, materials science, and nanotechnology applications. Chirality is a critical factor that defines the unique properties of Carbon Nanotubes (CNTs). CNTs exist in armchair CNTs, zigzag CNTs, and chiral CNTs (Figure 2(a)). CNTs exist broadly in two different configurations: Single-Walled Carbon Nanotubes (SWCNTs) with a tube diameter typically in the range of 1 to 2 nanometers and Multi-Walled Carbon Nanotubes (MWCNTs) composed of multiple concentric graphene layers (cylinders) nested within each other. The outermost wall of MWCNTs has a larger diameter than the innermost wall, and the number of walls can range from 2 to over 100 (Figure 2(b)). The properties of SWCNTs can vary depending on their chiral angle, which affects their electrical conductivity. MWCNTs typically have a larger diameter than SWCNTs and exhibit different mechanical properties, such as greater strength and resilience. CNTFET emerged as one of the major advanced and efficient technologies in integrated circuit (IC) design. Unlike MOSFETs and FinFETs, CNTFETs are not widely used commercially due to their high cost and fabrication challenges. The key difference between CNTFETs and MOSFETs lies in channel material: CNTFETs are quasi-ballistic devices utilising multiple CNTs as the alternative channel material as a replacement for bulk silicon, enabling higher carrier mobility, high current density, low self-heating and thermal noise due to their novel structural and electrical properties [20]. Moreover, the carbon nanotube channel is undoped; however, the heavily doped source and drain terminal noticeably reduces the OFF-current (leakage current). This makes CNTFETs an exceptional choice for low-power, high-performance system designs. Experiments and research studies show that CNTFETs' switching speed is hundreds of times faster than planar MOSFETs and about three times faster than FinFETs while using the same power. Thus, CNTFETs can operate at extremely high frequencies and are considered a contending option for next-generation VLSI design [20, 21].

The performance of portable devices is closely linked to battery life, and the number of transistors per chip has rapidly increased with transistor miniaturisation. Short Channel Effects (SCEs), which significantly impact power consumption when transistors are turned off, have become a major challenge for CMOS technology beyond 22 nm. To address these SCEs, technologies such as Fin-Shaped FETs, Tunnel FETs, and CNTFETs have emerged as advancements [22]. In today's rapidly advancing semiconductor industry, the channel length of MOSFETs has been reduced to increasingly smaller dimensions, ranging from a few micrometres to below 14nm. As a result, Si-based MOSFETs may no longer be relevant as performance enhancers in digital applications [23].

Moreover, minimising power consumption while maintaining precision is a key requirement for biomedical devices. Carbon Nanotube Field-Effect Transistors (CNTFETs) use Carbon Nanotubes (CNTs) as the channel material instead of traditional silicon (Figure 2(c)). Therefore, the CNTFETs offer superior speed, scalability, and power efficiency, making them promising candidates for future nanoelectronics. Integrating CNTFET-based Operational Transconductance Amplifier – Capacitor (OTA-C) circuits holds great promise for biomedical applications. The unique properties of Carbon Nanotubes (CNTs) enhance the performance of OTA-C circuits, which are crucial for signal amplification and filtering in medical devices. CNTFETs enable the design of high-speed, low-power biosensors, implantable devices, and wearable health monitoring systems, offering superior performance to traditional silicon-based MOSFET circuits. Furthermore, an active device like CNTFET-OTA-C can be utilised to design a notch filter that eliminates biological signal noise within a specific frequency range [19, 24, 25]. CNTFET-OTA-C could significantly suppress Power-Line Interference (PLI) during bio-signal recording, helping preserve the signal quality [26]. Therefore, the present research assessed the impact of CNTs as channel materials on the performance of the proposed power-efficient CNTFET-based OTA-C suitable for biomedical applications at different technology nodes.

Although some studies have examined the performance of different FET technologies at different nodes, like CNTFET- and CMOS-based OTAs at 32nm, 45nm, and 95nm nodes, a detailed assessment between CNTFET-based OTAs specifically at the 14nm and 22nm nodes is still lacking. Additionally, much of the existing CNTFET research has mainly focused on digital electronics and chemical sensor applications [27]. Despite advancements in CNTFET technology, little effort has been made towards the benefits of the CNTFET-based analog nano-electronic circuits [28], highlighting a notable research gap in the field. Subsequently, this study objects to design, simulate, and assess the performance of a power-efficient CNTFET-based OTA-C for biomedicine applications at the 14nm, 22nm, and 45nm technology nodes. The objective is to extend the understanding of the strengths and trade-offs of three distinct nodes using CNT-based OTA architecture. Moreover, achieving high performance, power efficiency, and signal integrity in CNT-based OTAs necessitates precise optimisation of channel width, length, and CNT parameters. Selecting the right channel dimension plays a crucial role in balancing transistor amplification of signals, leakage currents, and switching characteristics, all of which are essential for ensuring reliability in biomedical devices.

Additionally, key CNT features (diameter, chirality, and density) have a substantial impact on the transistor's threshold voltage, charge carrier mobility, and overall device behaviour. Carefully controlling these parameters enhances power efficiency and scalability and reduces noise, all of which are essential for wearable and implantable medical devices. To refine such design choices, a systematic evaluation process is employed, helping to tailor an optimised setup for biomedical electronics. Additionally, the CNT's diameter influences the bandgap (Eg), carrier mobility and voltage-threshold, which in turn influence transconductance and leakage currents [29]. The interspacing between CNTs, known as pitch, affects their density, current drive, and parasitic capacitance. Higher density can boost performance, but it may cause screening effects. Optimising these factors helps improve gain, power efficiency and noise performance in CNTFET-based OTA.

1.2. Comparison of CNTFETs with the Existing Traditional Technology (CMOS)

Traditional MOSFET-based OTAs faced serious challenges at advanced technology nodes owing to short-channel effects, higher leakage currents, and lower carrier mobility, all of which degraded overall FET performance. Their limited gain, high power consumption, and increased noise restrict their suitability for low-power implantable medical devices. As MOSFET devices shrink to the nanoscale, they become more sensitive to variations in manufacturing, resulting in performance degradation because of short-channel effects, for instance, Drain-Induced-Barrier-Lowering (DIBL), impact ionisation, and velocity-saturation. Hajare et al. showed that Fin-FET and CNTFET technologies both improve performance and scalability at the 14nm node. However, Fin-FETs still face performance limits beyond 14nm, which can impact overall Integrated Circuits (IC) performance. On the other hand, CNTFETs revealed better performance compared to Fin-FETs and are proposed as a strong alternative for technologies beyond 14nm. They could help the silicon industry by enabling low-power, high-performance (IC) [30]. Numerous foundries are exploring different nanoscale devices to achieve the best circuit performance, including nanowire FETs, graphene FETs, Tunnel-FETs (TFETs) [31, 32], and multi-gate transistors like Fin-FETs [33]. Among these, CNTFETs stand out as the most promising choice [34], due to their ultra-thin body form, smaller diameters, low OFF-current, excellent carrier mobility, aggressive channel length scaling, ballistic conduction, and semiconducting properties [35, 36]. CNTFETs have nearly 80 times greater conductivity compared to that of copper. CNTFET's electron-mobility and hole mobility outshine these mobilities in silicon, allowing for near-ballistic/quasi-ballistic carrier-transport within the nanotube [37]. By addressing the issues and limitations of existing technology, CNTFETs prove to be a superior choice for next-gen biomedical electronics and lower power electronics.

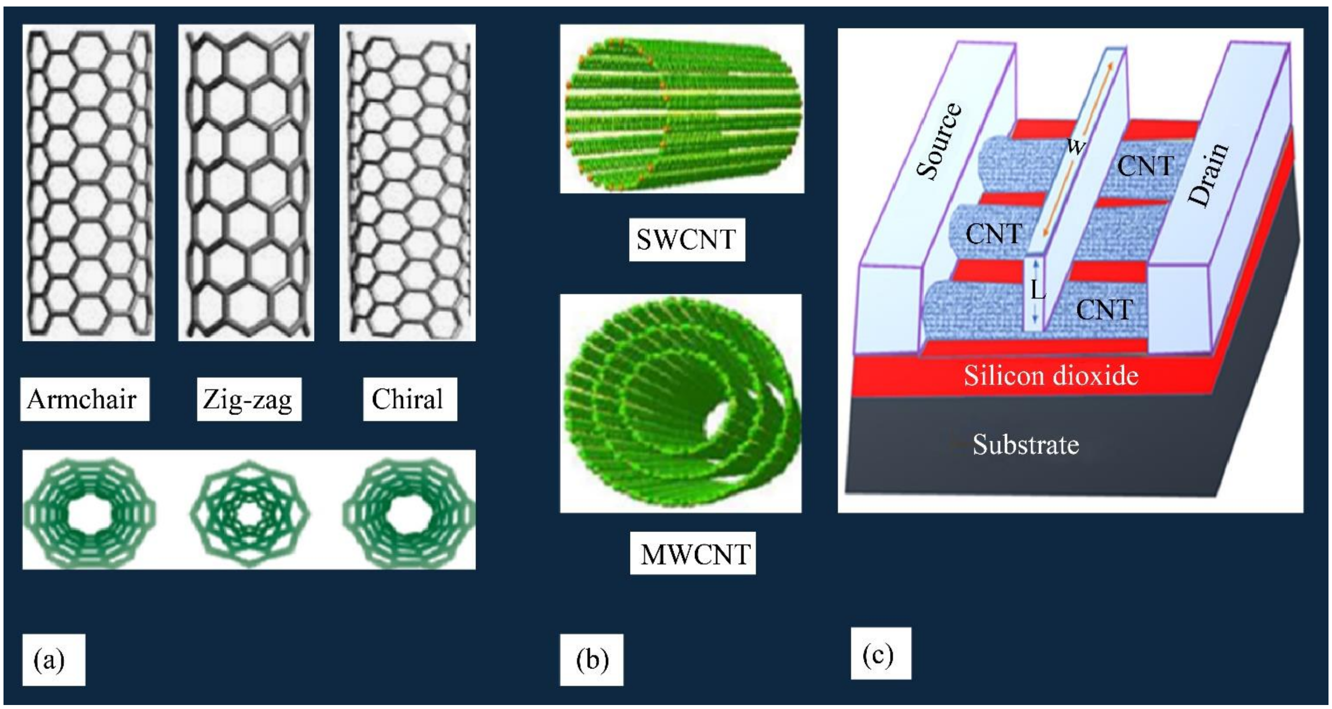

Fig. 2 Forms and configurations of the CNT (a) Different forms of the CNT, (b) CNT configurations, and (c) CNTFET with CNTs as channel material

2. Research Methodology

The Hspice simulation tool was used to conduct simulations for the proposed CNTFET-based OTA-C models to assess the impact of CNTs as channel materials on their performance across three technology nodes; the configuration (Figure 3) and simulation parameters are outlined below.

2.1. The Proposed CNTFET-Based OTA-C and Simulation Criteria

The present study configured the CNTFET-based OTA-C model using pure CNTs as channel material integrated into all the transistors. The proposed CNTFET-based OTA-C were designed across three technology nodes: 14 nm, 22 nm, and 45 nm, and simulation was accomplished using HSPICE. The CNTFET-based OTA-C was designed by taking the values of Channel Lengths (L = 14 nm, 22 nm, and 45 nm) and chirality (19, 0). However, for the quantitative impact assessment of CNTs on performance, CNTFET-based OTA-C, the number of CNT-tubes/transistor varied within a range of 1-20 CNTs/transistor. To simulate the CNTFET-based OTA-C, the simulation parameters used were capacitive load/CL = 1 pF, supply voltage of 0.9V, pitch (S = 20 nm), CNT diameter (DCNT = 1.5 nm) and a varying number of CNTs. Other significant simulation parameters pertaining to the Stanford model are summarised (Table 1). The OTA-C was configured by using a total of 9 transistors, out of which five NCNTFETs were used as sinks and five PCNTFETs were used as sources, as illustrated in Figure 3.

Table 1. CNTFET parameters used for simulations (using Stanford model)

S.No.	Parameter Name	Description	Value
1	m, n	Chirality	19,0
2	Lss	The source-side extension region, doped CNT length	7 nm
3	Ldd	The drain-side extension region, doped CNT length	7 nm
4	High-Kox	The dielectric constant of the top-gate dielectric material (HfO2)	16
5	Ef_i	Doped n+/P+ source/drain CNT-region Fermi level	0.6 eV
6	Pitch (S)	The distance between the neighbouring CNTs (integrated within the same device)	20 nm
7	Tox	oxide-thickness with High-k-dielectric	4 nm
8	Csub	The CNT to substrate (SiO2) coupling capacitance	40 aF/µm
9	dielectric constant	The dielectric constant of the substrate (SiO2)	4
10	Lgeff	The mean free path in intrinsic CNT	11 nm
11	Leff	The mean free path in p+/n+ doped CNT.	15 nm
12	Phi_M	Metal work function	4.6
13	Phi_S	CNT work function	4.5
14	Sub_pitch	Sub-lithography full pitch	6.4 nm

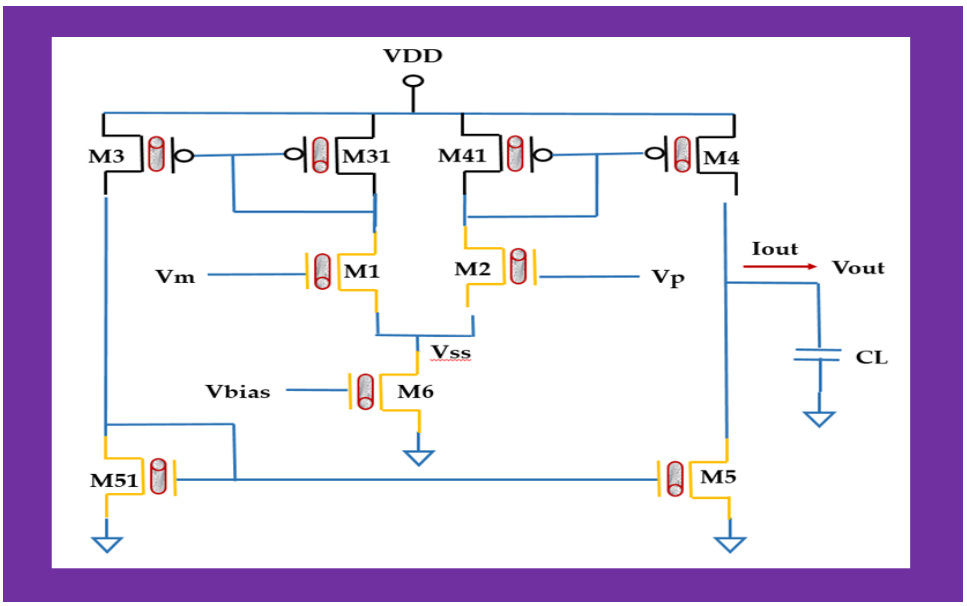

Fig. 3 Configuration of proposed CNTFET-based OTA-C

3. Hspice Simulation Results

Recent advances in Carbon Nanotube (CNT)-based nano-electronic circuits offer unique geometric and electronic benefits. However, designing systems that achieve both high gain and low power consumption is challenging due to conflicting requirements. This balance is particularly vital for portable biomedical devices, where low power and high gain highlight the need in low-voltage conditions. High gain is essential for low-voltage applications to ensure precise accuracy. The current research attempted to simulate CNTFET-based OTA-Cs across the 3 technology nodes, and the performance parameters were analysed comparatively to determine a high-gain, low-power architecture suitable for biomedical applications. The gain achieved upon simulations of proposed CNTFET-based OTA-Cs across technology note 14 nm, 22 nm, and 45 nm by varying the number of CNTs to assess the impact of CNTs on the performance of the OTA-Cs while keeping the rest of parameters constant was observed to increase with the number of CNTs that could be explained by the fact that adding more CNTs improves current conduction and transconductance, reducing effective channel length, enhancing electron mobility, and increasing gain (right side view of Figure 4(a), 4(b), Figure 5(a)) [38]. Moreover, the CNTFET current is dependent on the number of CNTs, which can be represented by Equation (1).

$$I_{CNTFET} \approx N.g_{CNT}\,(VDD - Vth\,) / (I + g_{CNT}\;\, L_s\,\rho_S) \qquad (1)$$

Where ICNTFET is the current of CNTFET, N is the number of CNTs, gCNT is transconductance/CNTFET, ρS is the source resistance per unit length of doped CNT, and Ls is the source length [38]. However, this must be balanced with power consumption and stability for optimal performance.

Our results revealed that the gain was stabilised around 16-20 CNTs in the case of OTA-Cs across the technology node. The maximum gains obtained at 20 CNTs were 44.429 dB, 38.159 dB, and 25.289 dB at 14 nm, 22 nm, and 45 nm at the technology nodes, respectively (left side view of Figure 4(a), 4(b), Figure 5(a)), which suggested the remarkable performance of the CNTFET-based OTA-Cs at technology node of 14 nm and 22 nm compared to the 45 nm. Most of the research compares the performance parameters of CNTFET-based OTA with MOSFET-based OTA at technology nodes 130 nm [38], 45 nm and 32 nm [39]. However, the information on the gain obtained by CNTFET-based OTA-C at 22 nm and 14 nm is scant. Thus, the present study's findings offer valuable insights that enrich and expand the current body of knowledge.

One of the key structural parameters of the CNTFET that significantly impacts the performance of CNT-based devices has been identified as the number (N) [40]. Consequently, N is varied from 1 to 20 while maintaining a fixed chirality vector (m, n) equal to (19, 0), Pitch S = 20 for every CNT-based-design simulation in this study (supplementary). Since an increment in N is just analogous to an increment in the MOSFET width, which enhances the current-driving-capability of a CNTFET, but also leads to higher average power dissipation and lower output Resistance (Ro), it can be a challenge in a CNT-based circuitry [41]. The gain increases with an increase in CNTS in CNT-based OTAs (as illustrated in Figure 4), but sadly, it also elevates the average power dissipation (Figure 6). Furthermore, DC gain increases with an increase in Pitch (S); however, after N = 20, it tends to remain nearly constant, whereas bandwidth experiences only a slight increase with the increase in CNT pitch [41]. Thus, the number of CNTs (N=20) and S=20 nm were optimised to achieve an optimal performance, i.e. high gain (44.429 dB, 38.159 dB, and 25.289 dB), low average power (13.47μW, 59.09μW, and 68.56μW) and low bandwidth in KHz (51.3 KHz, 522 KHz, and 3046 KHz) at 14 nm node, 22 nm node, and 45 nm node, respectively. These results demonstrate that the designed OTA at 14nm has attained the most favorable performance parameters, with the highest of gain 44.4 dB, highest output resistance of 18.5KΩ and lowest Avg. power of 13.47μW, and lowest bandwidth of 51.3KHz among all three CNTFET-based OTA designs, making it ideally suited for low amplitude and low frequency signal processing units [42].

Phase margin is a key indicator of stability in control systems and electronic circuits, particularly in amplifiers and feedback systems [43]. It is the additional phase lag required to bring the system to the verge of instability. A low phase margin indicates that the OTA is near instability, where even small changes can cause undesirable behaviours, such as oscillations or excessive overshooting of the output signal. A high phase margin (typically greater than 45-60 degrees) indicates a more stable response to input signals, meaning the OTA is less likely to experience oscillations or ringing, even under load variations or temperature changes [44]. Our result exhibited that the phase margin decreases with an increase in the number of CNTs. The decrease in phase margin was smooth and stabilised around 15 to 20 CNTs at technology nodes 14 nm and 22 nm; however, it did not stabilize at the 45 nm node because higher transconductance and faster response times can lead to instability, increasing phase shift and making the system more prone to oscillations (Figure 5(b)) [45]. While more CNTs improve gain, they can compromise stability, reflecting the need for a balance between these two parameters, which could be prioritised during the design of the CNTFET architecture. The phase margins obtained at 14 nm, 22 nm, and 45 nm were 90.336 degrees, 90.697 degrees, and 93.111 degrees, respectively (Figure 5(b)), indicating good stability of all the OTA-Cs, as the phase margin is slightly different across the technology nodes. Since a high phase margin (>60) generally correlates with better stability, ensuring that the OTA performs reliably over time and under varying conditions [46, 47]. Our finding corroborates the stability analysis of OTA reported by Shah et al. [48].

Laouej et. al. have designed a 0.18μm telescope OTA which has shown a good circuit stability with a phase margin of 80.8° along with a high gain (64dB), satisfying biomedical system design requirements [49]. Hesari et. al. have designed a 180 nm CMOS using a 0.8V supply. Results have shown a phase margin of 85.8°, a unity gain bandwidth of 108.3 MHz and a gain of 70 dB, proving it an ideal candidate for biomedical applications like a charge amplifier for apnea detection [50]. Cen et al. have designed a 32nm CNTFET OTA with a phase margin of 85° (along with a DC gain of 21.34 dB, Power consumption of 25μW, and bandwidth of 9.5 MHz) using a 0.9 V supply voltage. Their results have shown that a designed OTA can be used for filter designing and nanoscale low-power system designs [51]. Therefore, our proposed OTA at 14nm with a phase margin of 90.336°, exceeding the threshold for stability requirement of 45°, and even a phase margin above 60° is preferred for better stability [23]. This indicates that, based on the phase margin along with high DC gain, the proposed 14nm CNTFET-OTA is highly stable, due to the excellent performance of the designed device, all without compromising power dissipation and bandwidth, which are essential parameters for biomedical system designs [51].

Low power consumption in electronic circuits for biomedical applications is essential for improving device longevity, safety, comfort, and sustainability while ensuring reliable and efficient operation in healthcare settings [52]. Energy delivery, analog-to-digital conversion, signal processing, and communication subsystems are essential components of biomedical devices. Each crucial element requires an architectural design that minimises energy consumption to ensure suitability for biomedical applications [53]. Hence, circuit designs with minimal power consumption, ranging from microwatts to nanowatts, are recommended for biomedical applications [53]. Low power consumption extends the battery life of biomedical devices, particularly implantable ones [54, 55]. The current study showed a linear increase in power consumption with an increase in CNTs in CNTFET-based OTA-Cs across 14 nm node, 22 nm node, and 45 nm node (Figure 6(a)). Increasing the number of CNTs raises power consumption due to higher current drive, increased gate capacitance, and enhanced transconductance, all of which demand more energy for switching and operation, which explains the current result [38]. One of the research's significant aims was to tackle the issue of low power consumption by simulating and comparing CNT-based OTA-Cs at different nodes. The average power consumption of the CNTFET-OTA-Cs at 14 nm, 22 nm, and 45 nm was recorded to be 13.47µW, 59.09µW, and 68.56µW (Figure 6(b)), suggesting that the CNTFET-OTA-Cs at 14 nm node exhibited minimum power consumption with maximum gain fostering it suitable for biomedical applications [56], for instance implantable, wearable, POCT diagnostic devices [57, 58]. An OTA's unit gain frequency (UGF) measures the frequency at which the amplifier's open-loop gain drops to 1. It reflects the speed or bandwidth capability of the OTA, indicating how quickly it can respond to changes in the input signal while maintaining performance [59]. It also means that the OTA can be effectively used in high-frequency circuits, such as filters, oscillators, and communication systems, without substantial performance degradation from bandwidth constraints [59]. Achieving a high unit gain frequency, high phase margin, and low power consumption simultaneously is difficult, as a high UGF often comes with trade-offs, such as increased power consumption and reduced phase margin. If the circuit is not properly designed, this can result in stability issues, like oscillations. The unit UGF of the OTA-Cs at 14 nm, 22 nm, and 45 nm at CNT = 20 was recorded to be 7.7397 MHZ, 38.283 MHZ, and 50.472 MHZ, respectively. The low value of 7.7397 MHZ UGF of OTA-C at the 14 nm technology node implies that the Operational Transconductance Amplifier (OTA) has a limited bandwidth and can only operate effectively at lower frequencies than another technology node. This often results in slower response times and reduced performance at higher frequencies, but it may consume less power and have a higher phase margin, potentially improving stability [60].

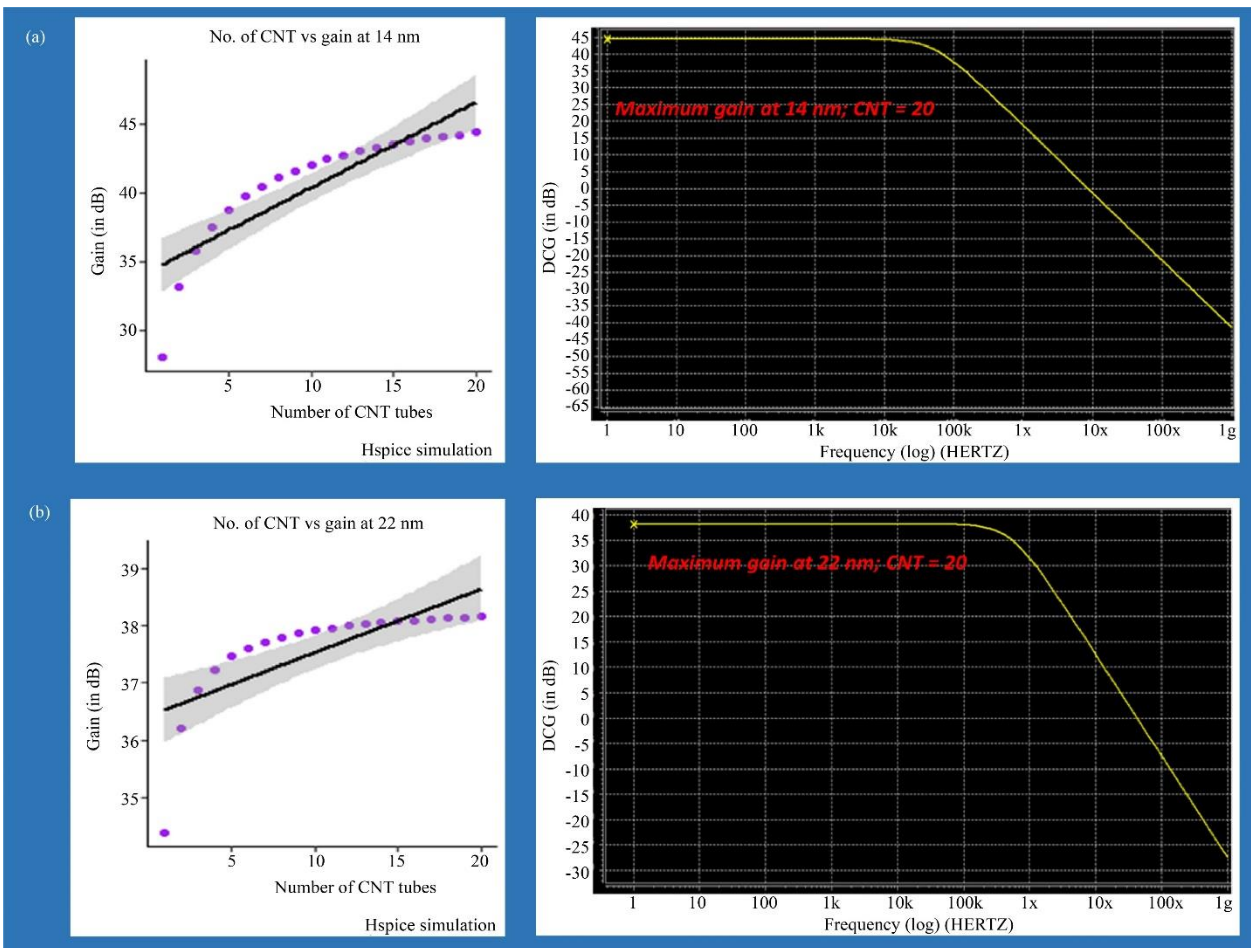

Fig. 4 Effect of CNTs variability on gain of CNTFET-based OTA-Cs and maximum gain obtained at CNT = 20 (a)- Effect of variations in CNTs on the gain of CNTFET-based OTA-Cs and maximum gain obtained at CNT = 20 at 14 nm technology node, and (b)-Effect of variations in CNTs on the gain of CNTFET-based OTA-Cs and maximum gain obtained at CNT = 20 at 22 nm technology node

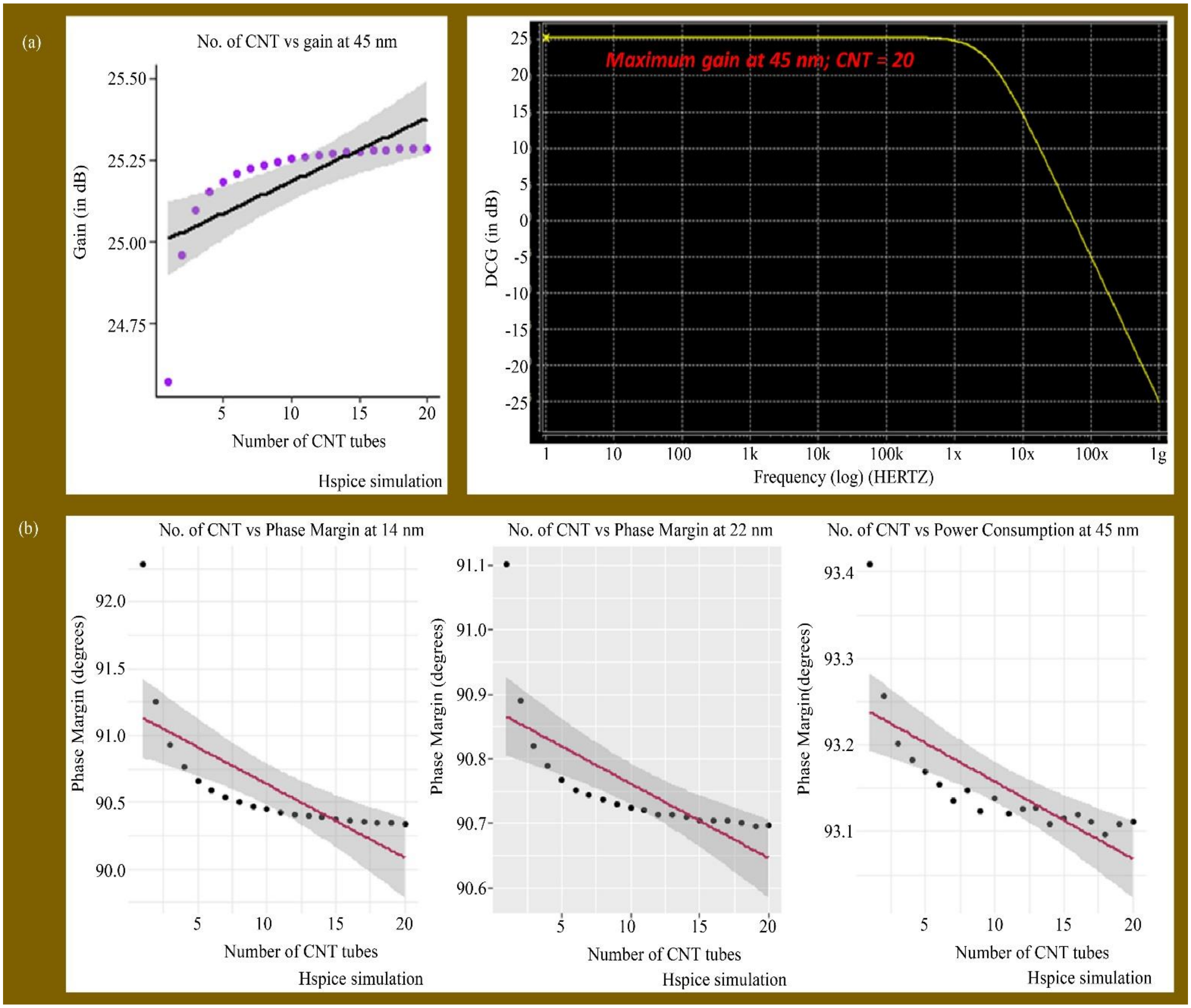

Fig. 5 Effect of CNTs variability on gain and phase margin of CNTFET-based OTA-Cs and maximum gain obtained at CNT = 20 (a)-Effect of CNTs variability on gain of CNTFET-based OTA-Cs and maximum gain obtained at CNT = 20 at 45 nm technology node, and (b)-Effect of variations in CNTs on the phase margin of CNTFET-based OTA-Cs across the technology node 14 nm, 22 nm, and 45 nm

Table 2. Performance parameters of all 3 CNTFET-based OTA-Cs at CNTs (N=20, S=20, VDD=0.9V, C_L=1 pF) across the technology nodes 14nm, 22nm, and 45nm, respectively

No. of CNTs	Performance parameters	Value at technology node 14 nm	Value at technology node 22 nm	Value at technology node 45 nm
20	Avg. Power	13.472μW	59.095μW	68.563μW
20	B.W (MHZ)	0.051390	0.52266	3.0460
20	Phase Margin°	90.33	90.69	93.11
20	Gain (dB)	44.29	38.15	25.29
20	UGF (MHZ)	7.7397	38.283	50.472
20	Gain Margin	-43.760	-37.244	-24.374
20	Gainmax	43.760	37.244	24.374
20	Ro (K Ω)	18.55	3.32	2.70

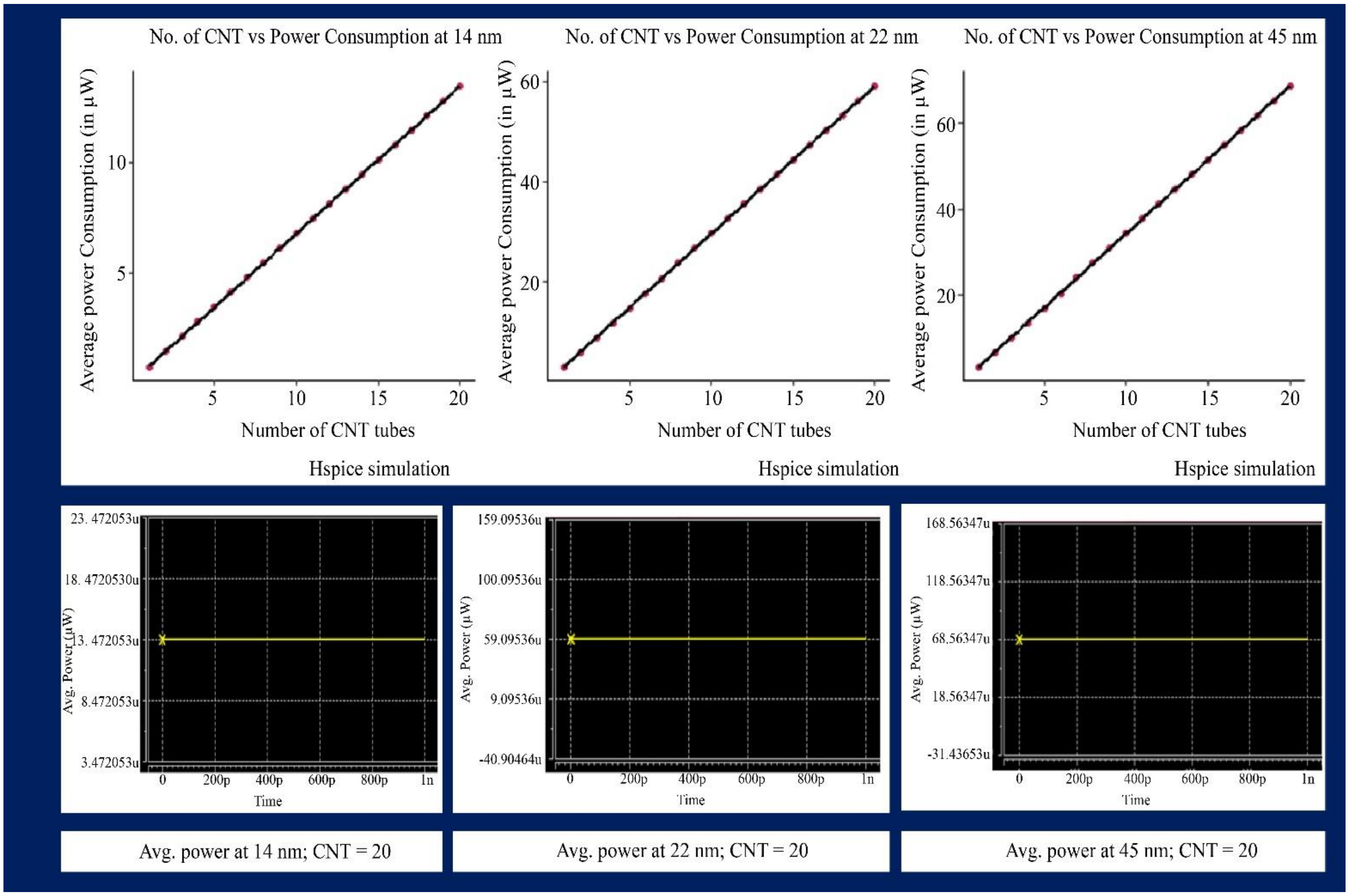

Fig. 6 Effect of variations in CNTs on the power consumption of CNTFET-based OTA-Cs at different technology nodes (a)- Effect of variations in CNTs on the power of CNTFET-based OTA-Cs at 14 nm, 22 nm, 45 nm, and (b)-Power-consumption of CNTFET-based OTA-Cs across the 14 nm node, 22 nm node, and 45 nm node obtained at CNT = 20

A low UGF can be suitable for biomedical signal applications because it typically operates at lower frequencies. Therefore, an OTA with a low UGF can provide sufficient bandwidth for processing these signals while potentially offering benefits such as reduced power consumption and improved stability, which are important in portable or wearable biomedical devices [61]. In addition to the critical parameters (gain, power consumption, phase margin, and unity gain frequency) of the proposed OTA-Cs, the effect of CNT variations on other dependent parameters—such as bandwidth, gain margin, maximum gain, and output resistance—of the CNTFET-based OTA-Cs across different technology nodes (14 nm, 22 nm, and 45 nm) was evaluated. The maximum values of bandwidth, gain margin, maximum gain, and output resistance for various CNT counts are summarized in Table 2. The effect of variations in the number of CNTs on these parameters is summarized in Table 2 and further detailed in the supplementary tables (Supplementary File)

4. Discussion

Recently, there has been significant progress in the development of high-performance, next-generation nano-electronic circuits based on carbon nanotubes (CNTs), which exhibit a distinctive combination of geometric and electronic properties [62]. Achieving a high-gain, low-power system presents a unique challenge due to the conflicting requirements for obtaining both low power consumption and high gain. However, the increasing demand for portable devices in biomedical applications has highlighted the need for circuit designs that balance low power and high-gain [63]. Moreover, high gain is essential for low-voltage applications to ensure precise accuracy [63].

Traditional techniques to enhance DC gain have been reported, such as cascading multiple stages and increasing output impedance. However, cascading can cause stability issues, and boosting gain increases output impedance, leading to higher voltage consumption and making it unsuitable for low-voltage applications [64]. Efforts are needed to design a building block to address and resolve the issue [65]. Hence, a low-power, high-gain amplifier is required for biomedical applications. The current research attempted to simulate CNTFET-based OTA-Cs across 3 technology nodes, and the performance parameters were analysed comparatively to determine a high-gain, low-power architecture suitable for biomedical applications. Assessment of the variation of the CNTS (N) on other dependent parameters, for instance, bandwidth, maximum gain, and output resistance of the CNTFET-based OTA-Cs across the technology nodes (14nm, 22 nm, and 45 nm) was also accomplished in addition to the critical parameters: gain, power consumption, phase margin, and UGF for the proposed OTA-Cs. The bandwidth, gain, gain margin, power requirement, UGF, gain maximum, and output resistance obtained at different numbers of CNT are summarised in Table 2.

The effect of variations in the CNTs on these parameters is tabulated in the Supplementary file. High gain of 40.3dB along with low Avg. power of 82nW, highly stable (phase margin = 89.4° and output resistance (Ro = 5.2KΩ) has been reported by Loan et al. in his design of CNTFET OTA-C at the 45 nm technology node; however, our result is at the 22 nm technology node. In one comparative analysis, the CNT-based OTA-C designed using 32 nm technology established a higher gain of 18.5 dB compared to its pure CMOS counterpart [66]. This research attempts to tackle the challenge of achieving low-power consumption by employing a simulation and comparing 3 different CNT-based OTA-C models. The current research findings suggest that all 3 CNTFET-based OTAs offer superior energy efficiency compared to MOSFET-based OTAs; however, the 14nm CNT-OTA, due to its lowest power consumption, makes it highly suitable for implantable and energy-constrained biomedical applications [67]. Their ability to operate at lower supply voltages (below 1V) significantly reduces power dissipation. This ultra-low power consumption is important for implantable medical devices like pacemakers and neural stimulators, as it helps in battery life extension, thereby minimizes the surgical interventions and maintenance costs [67]. Furthermore, CNT-based OTAs have less heat generation, avoiding damage to surrounding biological tissues, thus ensuring safe and long-term functionality within the body [68]. The 14 nm CNT-OTAs' low power requirements also make them compatible for integration with energy-harvesting technologies, paving the way for self-powered biomedical system designs, unlike traditional MOSFET-based OTAs with higher energy demands that often require frequent battery replacements [68]. Table 3 presents the performance comparison with previously published designs.

Table 3. An OTA performance comparison with other published work (at N=20, S=20nm, m=19, 0)

Technology	45nm-CMOS	32nm-CNTFET	14nm-CMOS	14nm-CNTFE	Proposed Work		
					45nm-CNTFET	22nm-CNTFET	14nm-CNTFET
Supply Voltage	0.5V	0.9V	0.9V	0.9V	0.9V	0.9V	0.9V
Load C_L	-	-	-	-	1 pF	1 pF	1 pF
DC Gain dB	45 (open loop)	30.86	17.7	30.7	25.28	38.15	44.429
Power	28.2 nW	5.94 nW	40.38µW	44.23 nW	68.53µW	59.09µW	13.47µW
Phase Margin°	-	-	90.36	94.36	93.11	90.69	90.33
Bandwidth	-	-	3.12 MHz	1.10 MHz	3.046 MHz	0.522 MHz	0.0513 MHz
UGF	-	0.55 MHz	-	-	50.47 MHz	38.28 MHz	7.7397 MHz
Output Resistance	-	145 KΩ	30.9 KΩ	48.9 KΩ	2.707	37.32 KΩ	18.55 KΩ
	[70]	[71]	P.W.	P.W.	-	-	-

5. Application and Future Perspective

The EMG signal is the combined action potentials detected near the electrode site, where muscle contractions cause its amplitude to increase, typically ranging from 0-10 mV peak-to-peak or 0 to 1.5 mV r.m.s value. The usable energy of such signals lies in the frequency range from 0 to 500 Hz, although the majority of its dominant energy is concentrated between 50 and 150 Hz [72]. Rani et al. have designed a 45nm CMOS OTA for use in ECG applications, utilising a 1V power supply, which yields a 56.6dB gain and a power consumption of 11.9 µW [73].

Rodrigues et al. have designed a CMOS 180 nm OTA using a 1.6V supply voltage with a power consumption of 194.33 nW, DC gain (dB) of 21.15, and phase margin of 62.6° for use in biomedical applications [74]. The proposed CNTFET-based OTAs using a low supply voltage of 0.9V at 3 different technology nodes (14nm, 22nm and 45nm) revealed potential for use in low-power applications. On comparing all three designs, 14nm CNTFET-based OTA is found to be best suitable for the biomedicine applications such as ECG, EEG, ERG and EMG due to its impressive characteristics including lowest power consumption (13.4µW), high gain (44.4 dB), low bandwidth (51.3 KHz), good stability i.e. phase margin (90.3°), small size of 14nm node and a high unit gain frequency (7.7 MHZ). Consequently, the 14 nm-node proposed OTA design is most suitable to impact the biomedicine sector, particularly applications such as sensors, notch filters, and low-pass filters, as OTA is the basic building block of a filter used in biomedical systems that operates at low frequency [75].

However, the unit gain frequency of the designed OTA can be large for bio-signals detection purposes; therefore, achieving optimal performance characterised in terms of unit gain frequency and increased gain margin while maintaining high gain, which could be achieved by varying the number and chirality of the CNTs. Experimental validation of the simulation results will be the future direction for this research. Moreover, future research will explore the development of various diagnostic and therapeutic biomedical devices utilising the proposed CNT-based OTA-C blocks.

6. Conclusion

OTA-based nanoelectronics is at the forefront of biomedical technology innovation, offering significant improvements in sensitivity, real-time signal processing, and low-power operation for various applications, from biosensors to neuro prosthetics. By advancing the integration of OTAs in nanoscale circuits, we could enable more precise, efficient, and affordable medical devices to improve health monitoring, diagnostics, and therapy, ultimately enhancing patient care and outcomes.

The current research assessed the impact of the variations in the number of CNTs on the critical performance parameters of the CNTFET-based OTA-Cs across the 14 nm, 22 nm, and 45 nm technological nodes, in addition to the determination of the high-gain, high-phase-margin and low power-consumption OTA-Cs suitable for biomedical applications at a specific number of tubes. It was observed that the OTA-Cs at 14 nm and 22 nm nodes were more stable, less power-consuming and more efficient in producing the desired DC gain compared to the OTA-C at the 45 nm technological nodes. Moreover, it was observed that the gain increased with the number of CNTs and stabilised around tube numbers 16-20 across 14 nm, 22 nm, and 45 nm nodes.

The average-power-consumption of the CNTFET-OTA-Cs at 14 nm node, 22 nm node, and 45 nm node was recorded to be 13.47µW, 59.09µW, and 68.56µW. The phase margins obtained at the 14 nm node, 22 nm node, and 45 nm node were 90.336 degrees, 90.697 degrees, and 93.11 degrees, respectively, which explains the stability of the OTA-Cs. OTA-C at the 14 nm technological node produced the lowest unit gain frequency, indicating that the OTA-C will operate efficiently on low frequencies.

The advantages of CNTFET-based OTA-C circuits in biomedical applications include improved signal fidelity, better energy efficiency, and compactness, which are essential for the miniaturisation of modern biomedical devices. However, fabrication, integration, and cost challenges must be addressed for large-scale adoption. This research provides new perspectives regarding the impact of different technology nodes on CNTFET-based OTA-Cs that could potentially guide future developments and applications in this domain.

The proposed 3 CNT-based OTAs at 3 different technology nodes have been compared. The performance measuring parameters of 14nm CNT-based OTA show a remarkable improvement in several performance-measuring parameters of analogue-signal processing, for instance, DC gain, average power, phase-margin, and unit-gain-frequency to be used in biomedical-circuitry. Further, it has been noted that the influence of CNTs plays a crucial role in CNT-based structures. Thus, optimizing the number of CNTs is essential to achieve an optimum performance.

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