Design of a Novel High Gain Carbon Nanotube based Operational Transconductance Amplifier

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Abstract—**In this work, design and simulation of novel operational transconductance amplifiers (OTAs) based on carbon nanotubes (CNT) has been performed. Two structures of CNT based OTAs have been proposed and have been compared with a conventional CMOS based OTA. The two CNT based OTAs include the one employing CNT based NMOS and conventional PMOS transistors, named as NCNT-PMOS-OTA and the other employing CNT based PMOS and conventional NMOS transistors, named as PCNT-NMOS-OTA. The proposed structures are designed using HSPICE and are based on 45 nm technology node. The key characteristics of the proposed devices, like DC voltage gain, average power, bandwidth and output resistance have been computed. It has been observed that CNT based OTAs result in high performance in comparison to CMOS-OTA. The DC gain has increased by 44.4% in PCNT-NMOS OTA and 69.3% in NCNT-PMOS OTA in comparison to CMOS-OTA. The average power has decreased by 24.18% in PCNT-NMOS OTA and 14.98% in NCNT-PMOS OTA in comparison to CMOS-OTA. The output resistance has also got significantly increased in CNT based OTA, however, has resulted in small bandwidth in comparison to conventional CMOS-OTA. Further, the simulation studies have revealed that the performance of the CNT based OTAs can be improved further by using an optimum number of CNTs (N).**

Index terms----Carbon nanotube, MOSFET, operational transconductance amplifier, simulation, dc gain, power consumption.

I. INTRODUCTION

One of the most important and widely used analog building block is the operational transconductance amplifier (OTA). This new class of operational amplifier (OP-AMP) has not only all the advantages and applications of the conventional OP-AMP, however, is has some extra advantages and applications. Apart from differential inputs, it contains additional control terminal which enhance its flexibility and application domain. The other advantages of OTAs include large bandwidth, large dynamic range, no excess phase issues, flexibility and tunability and realization of high integration level integrated circuits. The realization of CMOS based OTA has resulted in low power and high performance, however, the era of CMOS is nearing its end. The further scaling of MOSFET below 60 nm is becoming difficult due to short channel effects and other reliability issues. Besides, use of highly scaled MOSFETs to realize OTA results in poor linearity and limited output resistance. Therefore, there is an immediate need to address the scaling problems of the conventional MOSFET and enhance the validity of Moore’s law further. New efficient materials and devices need to be found to replace the existing silicon based MOSFETs.

One of the material and device of interest to researchers is CNT and CNTFET. CNT is being considered as a promising and is being projected to replace the widely used silicon. It has unique properties, like high tensile strength more than steel, electrical conductivity more than the best conductor silver, thermal conductivity more than diamond. One of the important properties is the presence of nearly 1D ballistic transport capability in a CNT. One of the important applications of CNT include the realization of a CNT based MOSFET, known as CNTFET. The CNTFET is a MOSFET like device with the channel replaced by parallel combination of CNTs. The CNT based channel results in very high mobility due to 1D ballistic transport of charge carriers and hence results in high drive capability to date.

To cash the advantages of CNTFET, we have realized OTA based on *N* and P type CNTFETs. In this work, two types of CNT based OTAs have been designed and simulated. In one case CNT based NMOS and conventional PMOS transistors have been used to realize an OTA, named as NCNT-PMOS-OTA. The second type of OTA uses CNT based PMOS and conventional NMOS transistors, named as PCNT-NMOS-OTA. Both these devices are designed using HSPICE and are based on 45 nm technology node. The important features of the proposed OTAs, like DC voltage gain, average power, bandwidth and output resistance have been computed. The simulation study has shown high performance in CNT based OTAs in comparison to conventional CMOS-OTA. The DC gain has increased by 44.4% in PCNT-NMOS OTA and 69.3% in NCNT-PMOS OTA in comparison to CMOS-OTA. The average power has decreased by 24.18% in PCNT-NMOS OTA and 14.98% in NCNT-PMOS OTA in comparison to CMOS-OTA. The output resistance has also got significantly increased in CNT based OTA, however, has resulted in small bandwidth in comparison to conventional CMOS-OTA. It has been further observed that the performance of the CNT based OTAs can be improved further by optimizing the number of CNTs (N).

The rest of the paper is divided into seven sections. In section II, brief overview of CNT and CNTFET has been given. Section III discusses briefly an OTA. In section IV,

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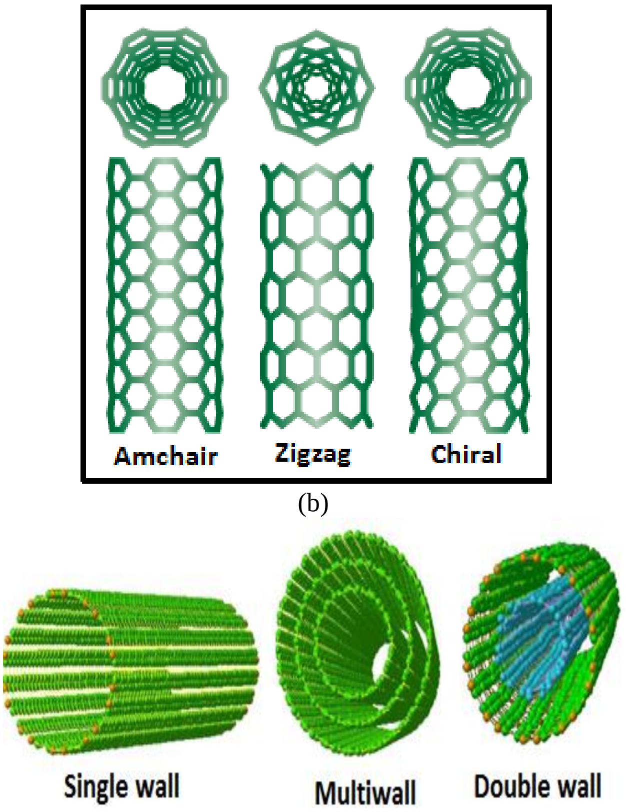
CNT based OTAs have been designed and analyzed. Finally, section V has concluded the paper.

II. CARBON NANOTUBE FIELD EFFECT TRANSISTOR

Carbon nanotubes were discovered by Ijima of NEC Japan in 1993, while studying the surface of graphite electrode in an electric arc discharge. They are actually allotrope of carbon. They possess unique electrical, mechanical and thermal properties. They are highly conductive (electrical and thermal) and have very high aspect ratio. Because of these unique properties they have wide domain of applications, including field-emission displays, nanocomposite materials, nanosensors, and nanoelectronics. The carbon nanotubes exist in two forms: (i) Single wall carbon nanotube (SWCNT) and (ii) multiwall carbon nanotube as shown in Figure 1(a). SWCNT are actually tubes of graphite that are normally capped at the ends. They can be visualized as a layer of graphite rolled into a seamless cylinder. Their diameter is around 1nm and length a few microns. They are superior to MWCNT, however, are costlier. MWCNT appear like a coaxial assembly of SWCNTs, like a coaxial cable. They diameter of MWCNT ranges from 5-50 nm and the inter layer spacing is 3.4Å. They are easy to produce in large quantity. However, the structure is complex and the structural imperfections may diminish their unique properties. The wrapping of graphite sheets in SWCNT can be represented by a pair of indices (n, m), called as the chirality vector or roll-up vector, as shown in Figure 1(b). There are three types of SWCNTs based on the chiral vector and chiral angle (θ). SWCNT is arm chair type if $n=m=0$ and $\theta=30^o$, it is a Zig-Zag if $n=m=0$ and $\theta=0^o$ and a Chiral type if n=/ m=/0 and θ lies between 0^o and 30^o



(b)

(a)

Figure 1. (a) Different types (b) different configurations of SWCNT

Figure 2 shows the schematics of one of the important application of CNT, that is, carbon nanotube field effect transistor (CNTFET). In a CNTFET, the channel is made up of parallel combination of SWCNTs. The source and drain regions are highly doped regions and the CNT channel is undoped. The important advantages of CNTFET include 1D ballistic transport of charge carriers, high mobility, large drive current and very low power consumption.

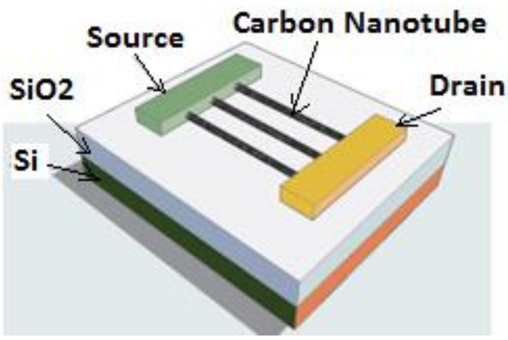


Figure 2. Schematics of a CNTFET

III. OPERATIONAL TRANSCONDUCTANCE AMPLIFIER

An operational transconductance amplifier is actually a voltage controller current source. OTA is similar to the conventional OP-AMP in many expect that an OTA has very high output impedance. An OTA posses an external bias current I_{abc}, which is responsible for the flexibility and tunability properties of an OTA. Figure 3 shows the symbol of an OTA. The OTA is best described in term of its transconductance (g_m) rather than voltage gain. The output current of an OTA is given by the following equation

$$I_{OUT} = g_m (V_1\text{-}V2) \qquad (1)$$

Where g_m is the transconductance, V1 and V2 are the two voltages at the input of the OTA.

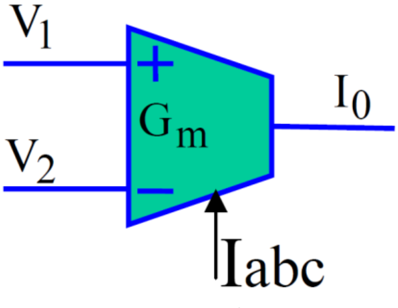


Figure 3. Symbol of an OTA.

IV. PROPOSED CNT BASED OTAS

In this work, two CNT based OTA have been designed and compared with the conventional CMOS OTA. Figure 4 shows a conventional CMOS OTA. The OTAs designed are based on 45 nm technology node and have been designed using HSPICE. Figure 5 shows the circuit diagram of one of the proposed CNT based OTA. It uses N CNTFETs as sinks and conventional PMOS transistors as sources. It is being called as PMOS-NCNT_OTA. Similarly, another proposed CNT based OTA uses P CNTFETs as sinks and conventional NMOS transistors as sources.

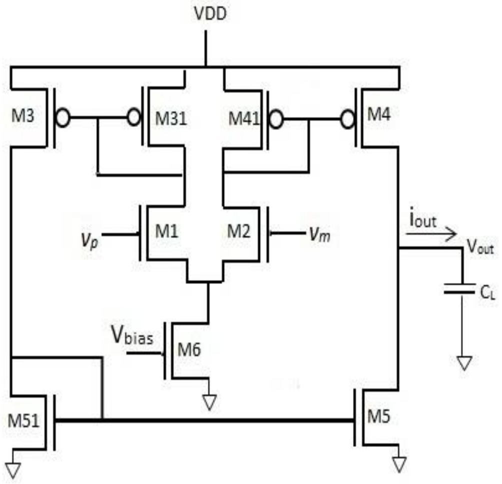


Figure 4. Conventional CMOS based OTA

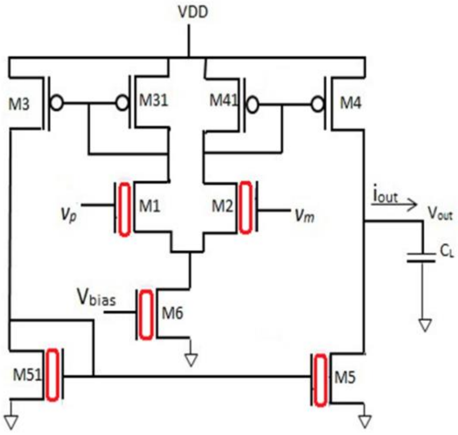


Figure 5. Proposed PMOS-NCNT-OTA

V. RESULTS AND DISCUSSION

In this work, the effect of change in number of transistors (N) on the overall performance has been studied for the two proposed CNT based OTAs. It has been observed that the number of CNTs change the performance significantly and an optimized number of CNTs need to be used to have an optimum performance. Figure 6 shows that the increase in number of CNTs increases the DC gain in both the CNT based OTAs. However, there is a saturation in the DC gain when N > 15. It may be due to screening effect due to large number of adjacent CNTs. Further, the DC gain in PMOS-NCNTFET-OTA is more in comparison to NMOS-PCNTFET-OTA. This can be attributed to large output resistance in PMOS-NCNTFET-OTA. Figure 7 shows that average power increases with the increase in number of transistors. This can be due to increase in drive current by increasing N. Figure 8 shows that the bandwidth increases with the increase in number of CNTs. Since increase in number of CNTs, increases transconductance and hence driving capability, therefore, bandwidth is bound to increase. The increase in bandwidth is more in NMOS-PCNTFET-OTA in comparison to PMOS-NCNTFET-OTA, due to low output resistance in NMOS-PCNTFET. Figure 9 shows that the output resistance decreases with the increase in number of CNTs in the channel. Since increase in number of CNTs is actually equivalent to increasing the width of a MOSFET, therefore, drive current increases and hence output resistance decreases.

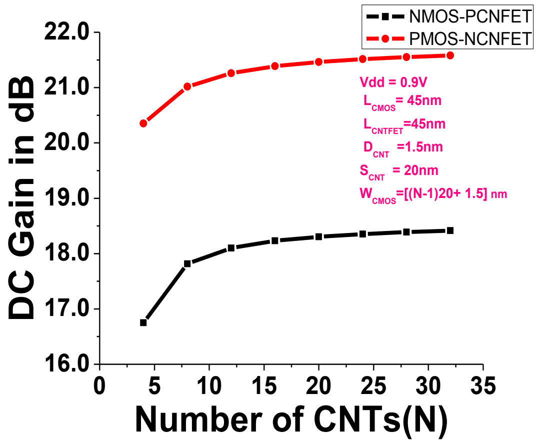


Figure 6. Variation of DC Gain with N.

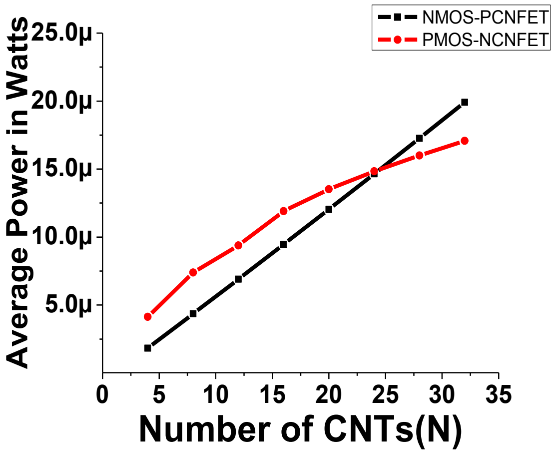


Figure 7. Variation of average power with N.

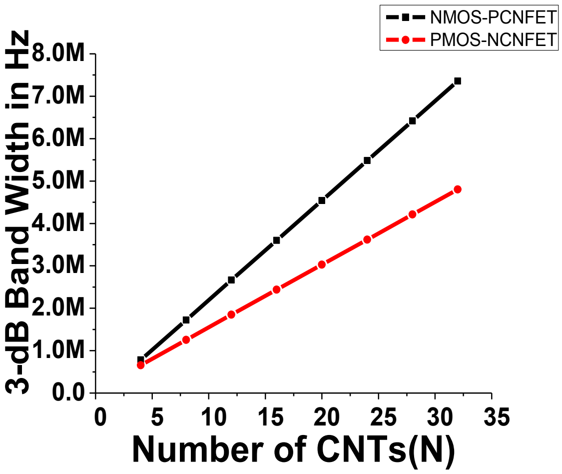


Figure 8. Variation of 3-dB bandwidth with N

Figure 10, Figure 11 and Figure 12 show the plots between gain and frequency of CMOS-OTA, NMOS-PCNFET-OTA and PMOS-NCNFET-OTA. It is seen that the gain is highest in CNT based OTAs. However, the bandwidth is low in CNT based OTAs in comparison to CMOS-OTA.

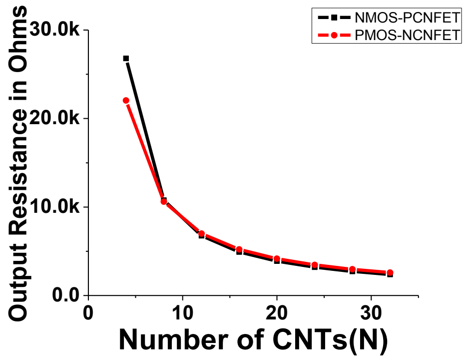


Figure 9. Variation of output resistance with the N

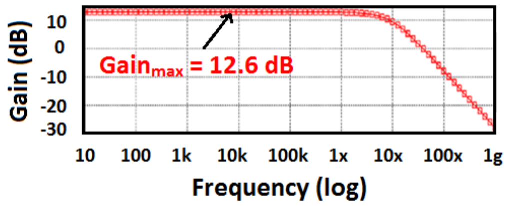


Figure 10. DC Gain plot of CMOS-OTA

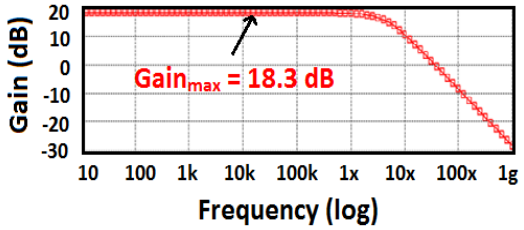


Figure 11. DC Gain plot of NMOS-PCNFET-OTA

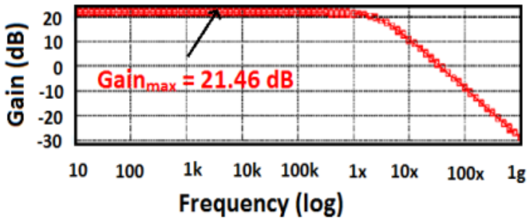


Figure 12 DC Gain plot of PMOS-NCNFET-OTA

VI. CONCLUSION

The work presents the design and simulation of OTAs based on CNTFET. Three OTAs have been designed and compared: (i) conventional CMOS-OTA (ii) OTA using conventional PMOS as loads and N CNTFETs as drivers (iii) OTA uses conventional NMOS as loads and P CNTFETs as drivers. The simulation study has revealed that the use of CNT in the conventional MOSFET will improve the performance significantly. The power consumption will decrease drastically, the speed will increase significantly and the DC gain will also increase significantly. Further, it has been seen that the performance of the CNT based OTAs can be improved further by using an optimum number of CNTs (N).

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