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High Performance Carbon Nanotube based Cascode Operational Transconductance Amplifiers

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***Abstract*—- In this paper, high performance carbon nanotube based Cascode operational transconductance amplifiers (COTA) have been designed and simulated. Two CNT based COTAs have been designed, one employing conventional PMOS sources and CNT based NMOS sinks, named as NCNT-PMOS-COTA and the other employing CNT based PMOS sources and conventional NMOS sinks, named as PCNT-NMOS-COTA. All the structures are designed using HSPICE and are based on 45 nm technology node. The performance of the proposed CNT based COTAs have been compared with the conventional CMOS based COTA. The comparative analysis has shown that the CNT based COTAs substantially outperform CMOS based COTAs. For example, the enhancement in DC gain is 17.41% in NCNT-PMOS-COTA and 10.56% in PCNT-NMOS-COTA; decrease in average power is by 54.15% in NCNT-PMOS COTA and 82.97% in PCNT-NMOS COTA in comparison to CMOS-COTA respectively. However, the output resistance has decreased in CNT based COTAs in comparison to conventional CMOS-COTAs. The low output resistance has resulted in a small bandwidth in CNT based COTAs. Further, it has been observed that the performance of CNT based Cascode OTAs can be improved significantly by optimizing number of CNTs in the CNTFETs used.**

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

I. INTRODUCTION

Operational transconductance amplifier (OTA) is one of the important analog signal processing block and has almost replaced operational amplifier[1-2]. The advantages of an OTA include more controlled nature due to presence of an extra control input, large bandwidth, large dynamic range and no excess phase issues. The flexibility and the tunability are the biggest advantages which are responsible for the extended application domain of an OTA. Further, with OTA, the realization of high integration level integrated circuits is highly possible [3-4].

However, the problems with the conventional OTA are related to gain and speed degradations in submicron range as the gain factor $g_m r_o$ degrades when the device dimensions are in submicron range. The gain factor degradation will be astronomically high in nanoscaled device [5-7].

The problem of gain degradation can be addressed by using the concept of cascading in OTA designing. Cascode amplifier configuration improves gain due to high output resistance and bandwidth due to reduced Miller capacitance [8-10]. Although Cascode OTA will result in high gain and high bandwidth, however, power dissipation is an important issue in it. 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 [11-15].

The power dissipation problem and the scaling issue can be significantly resolved by using carbon nanotube field effect transistors (CNTFET) instead of conventional MOSFET in OTA realization. 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 [16-25].

In this work, two CNTFET based Cascode OTAs (COTA) have been designed and simulated. The one CNT based COTA uses conventional PMOS sources and CNT based NMOS sinks, named as NCNT-PMOS-COTA and the other employing CNT based PMOS sources and conventional NMOS sinks, named as PCNT-NMOS-COTA. The simulation is being done by using HSPICE and all the structures are based on 45 nm technology node. The comparative analysis of the proposed CNT-COTAs with the conventional CMOS-COTA has shown a significant enhancement in DC gain of around 17.41% in NCNT-PMOS-COTA and around 10.56% in PCNT-NMOS-COTA. Further, the average power decreases by 54.15% in NCNT-PMOS COTA and 82.97% in PCNT-NMOS COTA in comparison to CMOS-COTA respectively. However, the output resistance has decreased in CNT based COTAs in comparison to conventional CMOS-COTAs. Further, it has been observed that the performance of CNT based Cascode OTAs can be improved significantly by optimizing number of CNTs in the CNTFETs used.

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

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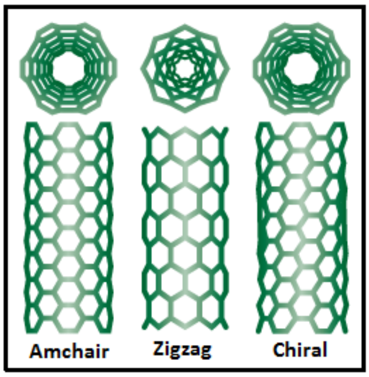
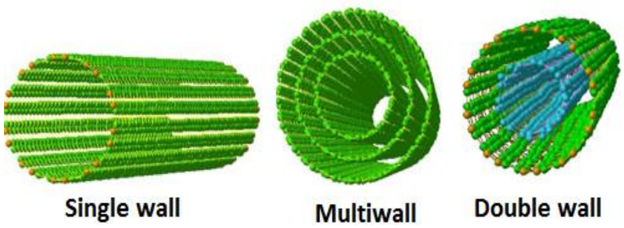
been discussed and analyzed in section V. Finally, conclusion is given in section VI.

II. CARBON NANOTUBE FIELD EFFECT TRANSISTORS

Carbon nanotubes were discovered by Ijima of NEC Japan in 1993, and are actually allotrope of carbon [16]. 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. 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 [18-20]. 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. The 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 [21-25].



(b)



(a)

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

Figure 2 shows the schematic diagram 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.

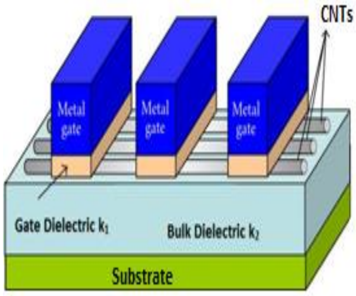


Figure 2. Schematic of a CNTFET

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 ways expect that an OTA has very high output impedance. It possesses 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 [1-2, 10]. 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

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

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

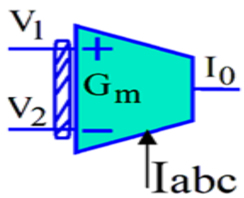


Figure 3. Symbol of a CNT-OTA.

IV. PROPOSED CNT BASED CASCODE OTA

We simulated two CNT based COTAs and compared the performance of the CNT-COTAs with the conventional CMOS COTA. Figure 4 shows a conventional CMOS based Cascode OTA. The COTAs 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 COTA. It uses N CNTFETs as sinks and conventional PMOS transistor as sources. It is being called as PMOS-NCNT-COTA. Similarly, another proposed CNT based COTA uses P CNTFETs as sources and conventional NMOS transistors as sinks and is being called as NMOS-PCNT-COTA. The figure of NMOS-PCNT-COTA is not shown here.

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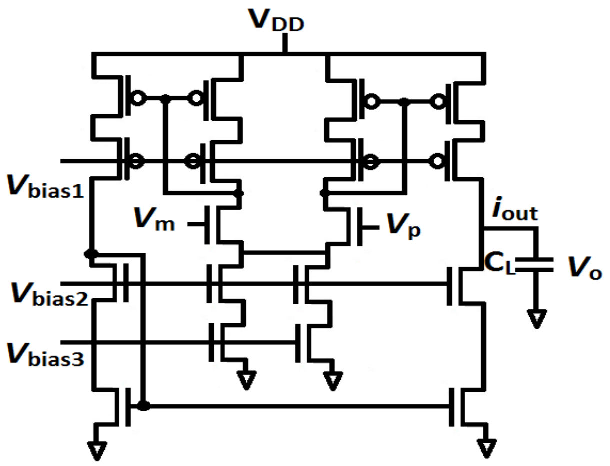

Figure 4. Conventional CMOS based Cascode OTA (COTA)

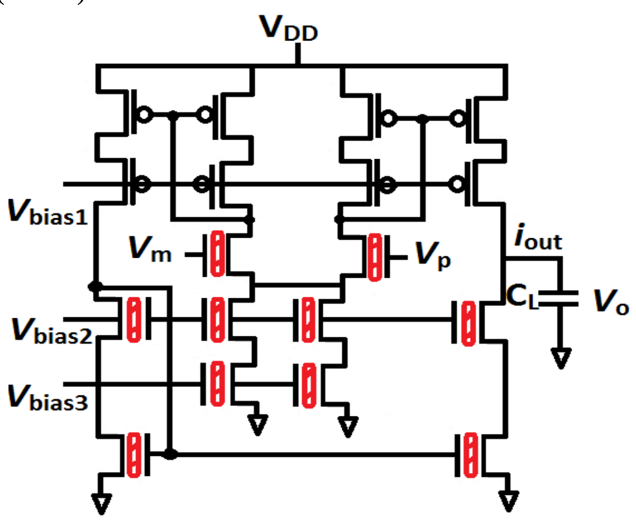

Figure 5. Proposed PMOS-NCNT-COTA

V. Results and Discussion

In the proposed CNT based COTAs, the effect of variation of the number of CNTs (N) on various performance measuring parameters have been studied. It has been seen that N changes performance significantly and its optimum value will result in an optimum performance. The effect of N on the DC gain of both PMOS-NCNT-COTA and NMOS-PCNT-COTA circuits is shown in Figure 6. It is clear from Figure 6 that with the increase in N, DC gain remains more or less constant (just around 2% variation in gain with 600% variation in N in NMOS-PCNT-COTA and less than 1% variation PMOS-NCNT-COTA). Though DC gain must increase with the increase in N due to increase in drive current/transconductance, however, reduction in output resistance and increase in screening effect with increase in N appears dominating always, and prevents the increase in gain. Further, the DC gain in PMOS-NCNT-COTA is more in comparison to NMOS-PCNT-COTA. This can be attributed to more number of N CNTFETS (ten) in PMOS-NCNT-COTA in comparison to just eight P CNTFETs in NMOS-PCNT-COTA. More CNTFETs will result in higher transconductance and hence higher gain. The decrease in gain can be attributed to decrease in output resistance with increase in N. On seeing the variation of bandwidth with N in Figure 7, it is clear that the bandwidth increases with the increasing N. Since gain and bandwidth are inversely related, decrease in gain must result in an increase in bandwidth, which is clearly seen in Figure 6 and Figure 7. Since increase in N, increases the drive current, therefore, bandwidth increases [22-25]. The increase in bandwidth is more in NMOS-PCNT-COTA in comparison to PMOS-NCNT-COTA, due to better switching by NMOS in comparison to PMOS and associated lower capacitance in NMOS [22]. 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 8 shows that the output resistance decreases with the increase in number of CNTs in the channel. The decrease in output resistance is more in PMOS-NCNT-COTA in comparison to NMOS-PCNT-COTA due to more number of n CNTFETS (10 CNTFETs) in PMOS-NCNT-COTA in comparison to NMOS-PCNT-COTA (8 CNTFETs).

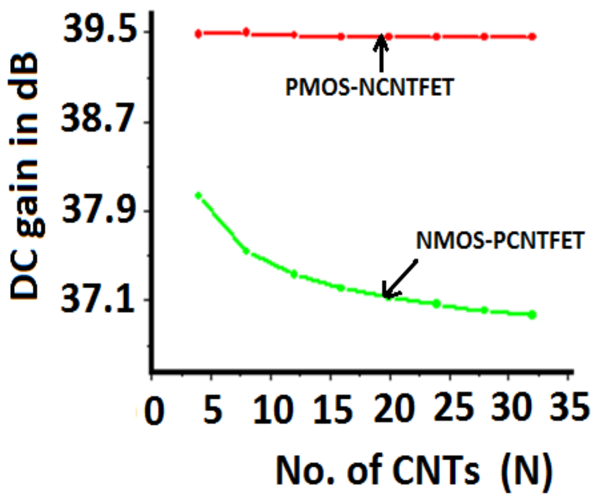

Figure 6. Variation of DC Gain with N.

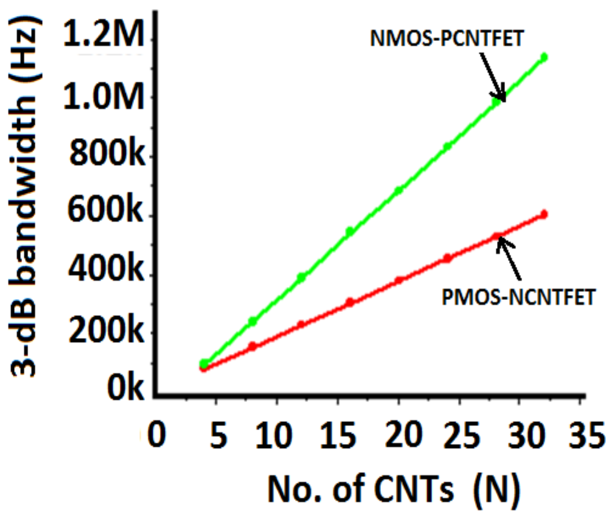

Figure 7. Variation of 3-dB bandwidth with N.

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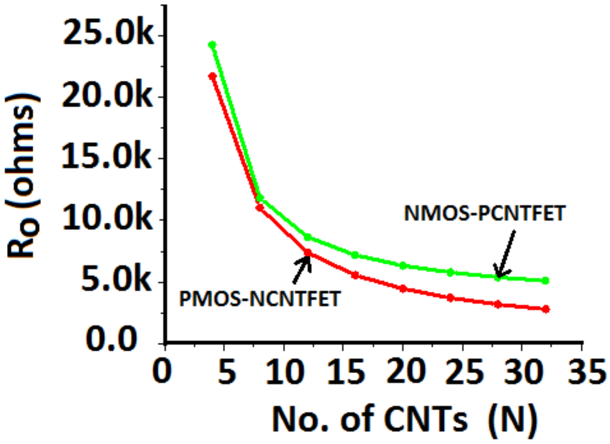

Figure 8. Variation of output resistance with the N.

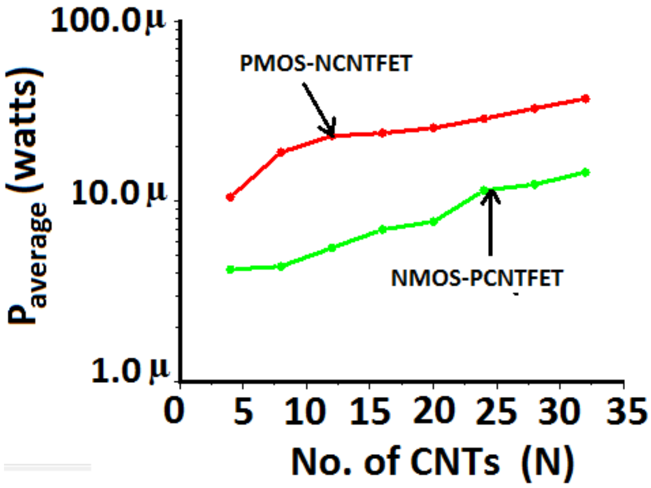

Figure 9. Variation of average power with N.

Figure 9 shows that average power increases with the increase in number of CNTs. This can be due to increase in drive current by increasing N. The average power is more in PMOS-NCNT-COTA. This can be due to more current due to more number of CNTFETs PMOS-NCNT-COTA. Figure 10, Figure 11 and Figure 12 show the plots between gain and frequency of CMOS-OTA, NMOS-PCNFET-COTA and PMOS-NCNFET-COTA. 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. The large gain in PMOS-NCNT-COTA can be attributed to its low output resistance. Table 1 shows the comparative analysis of various performance measuring parameters in the three types of OTAs.

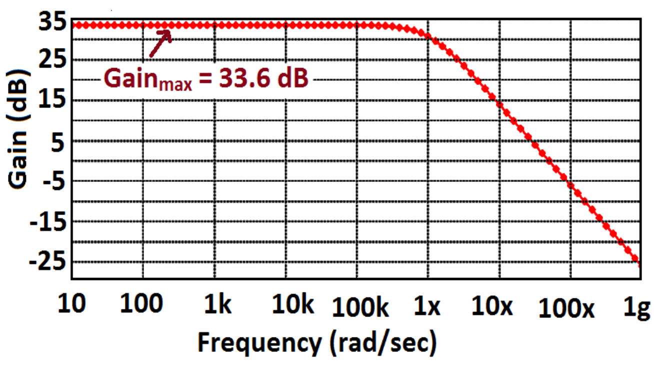

Figure 10. DC Gain plot of CMOS-OTA

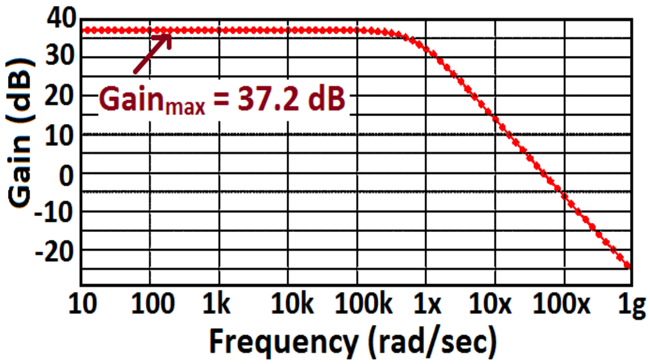

Figure 11. DC Gain plot of NMOS-PCNF-COTA

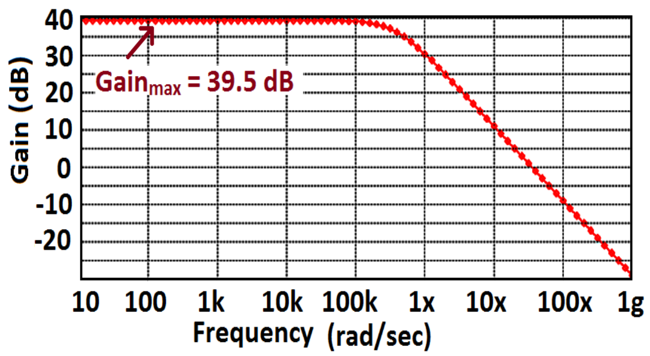

Figure 12 DC Gain plot of PMOS-NCNT-COTA

Table 1: Comparative analysis of COTAs with C_L = 1 pf , V_{DD} = 0.9V @ 45nm tech. node, N=20 , S=20nm, D=1.5nm.

S. No	Parameter	CMOS-COTA	PMOS NCNT-COTA	NMOS-PCNT COTA
1	DC Gain in dB	33.6	39.45	37.15
2	Average Power (uW)	55.68	25.53	9.48

VI. CONCLUSION

In this paper, simulation studies of high gain CNTFET based Cascode operational amplifiers have been performed. Two CNT based COTAs designed include NCNT-PMOS-COTA and the other PCNT-NMOS-COTA. All the structures are designed using HSPICE and are based on 45 nm technology node. The performance of the proposed CNT based COTAs has been compared with the conventional CMOS based COTA. It has been seen that significant improvement in parameters, like DC gain, bandwidth, power reduction, output resistance is achieved in the proposed COTAs. Further, it has been found that optimizing the number of CNTs in the CNTFETs used will further optimize the performance of COTAs.

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