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Design of Active Filters using CNTFET Opamp

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Abstract — **The main objective of this paper is to describe the work on modeling, performance benchmarking for nanoscale devices and circuits using Carbon Nano Tube Field Effect Transistors (CNTFETs), with the aim of guiding nanoscale device and circuit design. First, a compact model has been developed for MOSFET like Carbon Nanotube Field Effect Transistor (CNTFET) which posses high fabrication feasibility and superior device performance. The design aspects of a high performance CNTFET based operational amplifier are presented. This CNTFET op-amp is used for the realization of various active filters and the simulation studies have been done using Hspice.**

***Index Terms*— Active Filter, Carbon Nanotube Field Effect Transistor, Hspice, MOSFET, Op amp.**

I. INTRODUCTION

Aggressive scaling of CMOS circuits has led to higher and higher integration density, more functional complexity and better performance [1].Small size of the MOSFET, below a few tens of nanometers creates the low Trans-conductance, gate oxide leakage, low ON-current, Mobility degradation and increased delay CNTFETs are novel devices that are expected to sustain the transistor scalability while increasing its performance. One of the major differences between CNTFETs and MOSFETs is that the channel of the former devices is formed by CNTs instead of silicon, which enables a higher drive current density, due to the larger current carrier mobility in CNTs compared to bulk silicon[2][3].

Some researchers believe that the next nano transistor generations will be designed based on CNT elements, called CNTFET. This is because CNTs have been called the “wonder material of the 21st century, the building blocks for silicon circuits [4-8]”. While it is debatable whether the contacts and shorter channel length respect to Fermi wavelength confirm this grant prediction.

The main drawbacks of the MOSFET is that the sensitivity of a MOSFET’s gate to static and high-voltage spikes makes it vulnerable to damage resulting from parasitic oscillation. This undesired self-oscillation could result in excessive gate-to-source voltage that permanently damages the MOSFET’s gate insulation. Another MOSFET limitation is gate capacitance. This parameter limits the frequency at which a MOSFET can operate effectively. CNTFET overcomes these limitations to produce better performance than MOSFET.

In terms of the device operation mechanism, CNTFET can be categorized as either Schottky Barrier (SB) controlled FET or MOSFET-like FET [9]-[11]. Though good dc current can be achieved by SB-controlled CNTFET with the self-aligned structure, its ac performance is going to be poor due to the proximity of the gate electrode to the source/drain metal. The ambipolar behavior of SB-controlled CNTFET also makes it undesirable for complementary logic design. Considering both the fabrication feasibility and superior device performance of the MOSFET-like CNTFET as compared to the SB-controlled FET, we choose to focus on MOSFET-like CNTFETs in this work.

This paper is organized as follows. Section 2 introduces the Carbon Nanotube Field Effect Transistor. Section 3 describes the modeling aspects of MOSFET like CNTFET. Section 4 deals with the design of various active filters using CNTFET operational amplifier and Section 5 discuss the frequency response of the circuits designed in Section 4. Section 5 concludes the work undertaken in this paper.

II. CARBON NANO TUBE FIELD EFFECT TRANSISTOR

CNTs are sheets of graphene rolled into tubes. The single-walled CNT can be either metallic or semiconducting depending on the chirality (i.e., the direction in which the graphene sheet is rolled). Semiconducting nanotubes have attracted the widespread attention of device/circuit designers as an alternative channel implementation for high performance transistors.

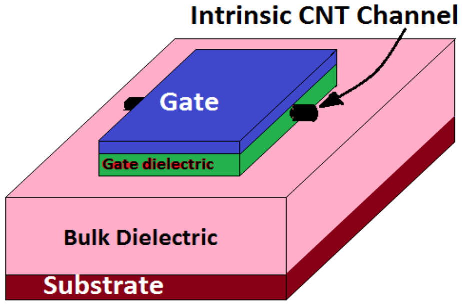

Figure 1: Structure of MOSFET like CNTFET

The structure of CNTFET is almost the same like silicon MOSFET except the CNT is attached in the transistor and acts as the channel. CNTFET operates on the same principle of MOSFET. The electrons travel from the source terminal to the drain terminal. In this paper, we focus on MOSFET-like CNTFET structure as shown in Figure 1.

The source and drain are heavily doped and hence, exhibits substantially improved performance. MOSFET-like CNTFET operates on the principle of modulating the barrier height by applying gate voltage. The drain

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current is controlled by the number of charge that is induced in the channel by gate potential.

III. SIMULATION MODEL OF CNTFET

The MOSFET-like CNTFET model used in this study is schematically shown in Figure 2.

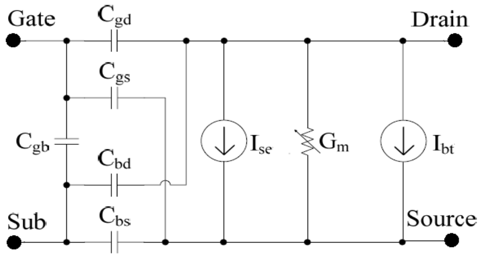

Figure 2: Equivalent circuit of MOSFET like CNTFET

A brief description of the theoretical analysis is given as follows. We assume near-ballistic transport and contacts in this work, i.e. $eV_{DS} \approx \mu_d - \mu_s$ so μ_s remains almost constant in the source-channel region and μ_d remains almost constant in the channel-drain region.

We consider three current sources in this CNTFET model: (1) the thermionic current contributed by the semiconducting sub-bands (I_{se}) with the classical band theory, (2) the current contributed by the metallic sub-bands (I_m), and (3) the leakage current (I_{bt}) caused by the band to band tunneling mechanism through the semiconducting sub-bands.

A. Current and Capacitance Expressions

The thermionic current contributed by the semi conducting sub-bands is given by,

$$I_{se}\left(V_{ch,DS}, V_{ch,GS}\right) = \quad (1)$$

$$\frac{4e^2}{h}\sum_{k_m}^{M}\limits_{m=1} T_m \cdot \left[V_{ch,DS} + \frac{kT}{e}\ln\left(\frac{1+e^{(E_{m,0}-\Delta\Phi_B)/kT}}{1+^{(E_{m,0}-\Delta\Phi_B+eV_{ch,DS})/kT}}\right)\right]$$

$V_{ch,DS}$ and $V_{ch,GS}$ denotes the Fermi potential differences near source side within the channel, e is the unit electronic charge, $\Delta\Phi_B$ is the channel surface potential change with gate/drain bias, T_m is the transmission probably, k is the Boltzmann constant and T is the temperature in Kelvin and $E_{m,0}$ is the half band gap of the mth sub-band.

For metallic sub-bands of metallic nanotubes, the current I_m includes both the electron current and the hole current,

$$I_m = 2(1-m0)T_{met}\sum_{k_l}^{L}\limits_{l=1}\left[J_{e\_0,l} + J_{h\_0,l}\right] \quad (2)$$

$$J_{e\_0,l} = \frac{2e}{h}\frac{\sqrt{3}a\pi V_\pi}{L_g} \quad (3)$$

$$\left(f_{FD}(E_{0,l} - \Delta\Phi_B) - f_{FD}(E_{0,l} + eV_{ch,DS} - \Delta\Phi_B)\right)$$

$$J_{h\_0,l} = \frac{2e}{h}\frac{\sqrt{3}a\pi V_\pi}{L_g} \quad (4)$$

$$\left(f_{FD}(-E_{0,l} - \Delta\Phi_B) - f_{FD}(-E_{0,l} + eV_{ch,DS} - \Delta\Phi_B)\right)$$

$f_{FD}(E)$ is the Fermi-Dirac distribution function, $f_{FD}(E) = \frac{1}{1+e^{E/kT}}$ and the transmission probability T_{met} is given by,

$$T_{met} = \frac{\lambda_{ap}\lambda_{op}}{\lambda_{ap}\lambda_{op} + (\lambda_{ap} + \lambda_{op}).L_g} \quad (5)$$

5)

L_g, the channel length , λ_{op} (~ 15 nm[13]), the optical phonon scattering mean free path (MFP) and λ_{ap} (~ 500 nm[14]), the acoustic phonon scattering MFP.

In the sub-threshold region, especially with negative gate bias (nFET), the band-to-band tunneling current from drain to source becomes significant. We include a voltage controlled current source I_{bt} in the device model in order to evaluate the device sub-threshold behavior and the static power consumption.

$$I_{bt} = \frac{4e}{h}kT \quad * \quad (6)$$

$$\sum_{k_m}^{M}\limits_{m=1} T_{bt}\ln\left[\left(\frac{1+e^{(eV_{ch,DS}-E_{m,0}-E_f)/kT}}{1+^{(E_{m,0}-E_f)/kT}}\right).\frac{\max(eV_{ch,DS} - 2E_{m,0}, 0)}{eV_{ch,DS} - 2E_{m,0}}\right]$$

To model the intrinsic ac response of CNTFET device, we use a controlled transcapacitance array among the four electrodes (G, S, D, B) with the Meyer capacitor model [15], thereby the equations for capacitance calculation are given as follows.

$$C_{bs} = C_{gs}\frac{C_{sub}}{C_{ox}} \quad (7)$$

$$C_{bd} = C_{gd}\frac{C_{sub}}{C_{ox}} \quad (8)$$

$$C_{gs} = \frac{L_g C_{ox}(C_{Qs} + (1-\beta C_c))}{C_{tot} + C_{Qs} + C_{Qd}} \quad (9)$$

$$C_{gb} = \frac{L_g C_{sub} C_{ox}}{C_{tot} + C_{Qs} + C_{Qd}} \quad (10)$$

$$C_{gd} = \frac{L_g C_{ox}(C_{Qs} + \beta C_c)}{C_{tot} + C_{Qs} + C_{Qd}} \quad (11)$$

C_{tot}, is the total electrostatic coupling capacitance per unit length between channel and other electrodes, C_{Qs} and C_{Qd} as the quantum capacitance due to the carriers from source (+k branch) and drain (−k branch), respectively.

IV. ACTIVE FILTERS

Active filters can have high input impedance, low output impedance, and virtually any arbitrary gain. They are also usually easier to design than passive filters. Possibly their most important attribute is that they lack inductors, thereby reducing the problems associated with those components. Still, the problems of accuracy and value spacing also affect capacitors, although to a lesser degree. Performance at high frequencies is limited by the gain-bandwidth product of the amplifying elements, but within the amplifier's operating frequency range, the op amp-based active filter can achieve very good accuracy, provided that low-tolerance resistors and capacitors are used.

The operational amplifier used in active filter circuit is designed using CNTFET with improved current voltage limiting and phase/frequency response extensions. The key CNTFET op amp parameters modeled using Hspice model are gain bandwidth product (GBP), slew rate (SR), phase margin, DC gain (A_D), CMRR, input offset voltage (V_{OS}), input bias current (I_B), input offset current (I_{OS}), output current limiting (I_{SC}), output voltage limits (V_{SAT}), output resistance (R_{OUT}), and power supply quiescent current (I_Q).

This paper illustrates some typical filter circuits such as low pass filter, high pass filter, band pass filter, band reject filter etc based on CNTFET opamp.

A. Low Pass Filter

A low-pass filter, shown in Figure 3, passes low frequency signals and rejects signals at frequencies above the filter's cutoff frequency. Low-pass filters are used whenever high frequency components must be removed from a signal.

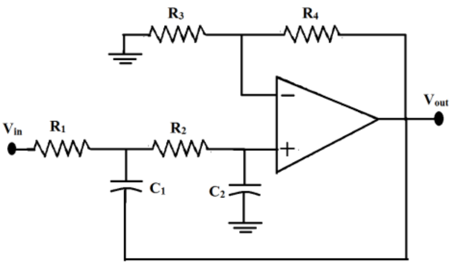

Figure 3: Low Pass Filter

The purpose of R_4 in Figure is to help counteract the DC offset of the operational amplifier that is created by input bias currents charging the capacitors in the frequency selective network. The value of R_4 in the unity gain case is 2R, where R is the value of the resistors in the frequency selective network. In cases where DC offset is not a problem, resistor R_4 can be replaced with a short circuit between the operational amplifier output and the inverting input. If pass band gain for the second order low pass filter is required then resistors R_3 and R_4 are used.

B. High Pass Filter

The opposite of the low-pass is the high-pass filter, which rejects signals below its cutoff frequency. High-pass filters are used in applications requiring the rejection of low-frequency signals.

The circuit of high pass filter shown in Figure 4 is similar to the low pass design except for a reversal of the roles of capacitors and resistors. The cut-off frequency is the frequency at which gains falls off -3db and is found from:
$f_c = 1/(2\pi[R_1R_2C_1C_2]^{1/2})$
The gain magnitude of the circuit is found from:
$V_0/V_{in}=A_v/[1+(f_c/f)^4]^{1/2}$

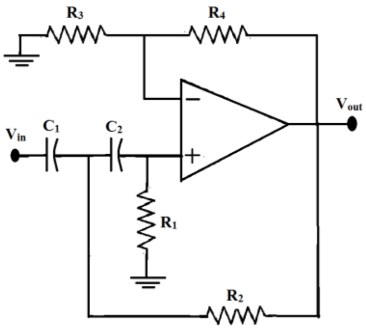

Figure 4: High Pass Filter

C. Band Pass Filter

Band pass filters are used in electronic systems to separate a signal at one frequency or within a band of frequencies from signals at other frequencies. Band pass filters have two stop bands, one above and one below the pass band. Such a filter could also reject unwanted signals at other frequencies outside of the pass band, so it could be useful in situations where the signal of interest has been contaminated by signals at a number of different frequencies.

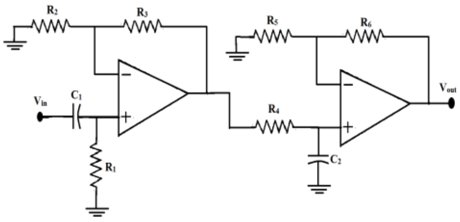

Figure 5: Band Pass Filter

First order band pass filter frequency responses is obtained by cascading first order high pass and low pass filter circuits as shown in Figure 5. This arrangement overlays or superimposes the frequency response characteristics of both filter stages into one stage.

D. Band Reject / Notch Filter

A filter with effectively the opposite function of the band pass is the band-reject or notch filter. Notch filters are used to remove an unwanted frequency from a signal, while affecting all other frequencies as little as possible.

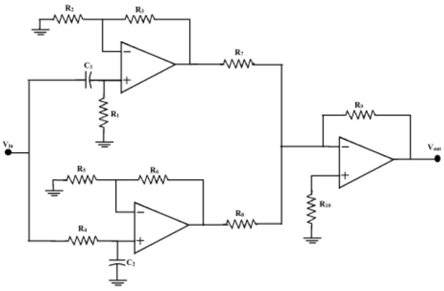

Figure 6: Band Reject Filter

Figure 6 shows a typical active notch filter. Note that the gain is constant throughout the frequency spectrum except in the immediate vicinity of $f_{c.}$ The depth of the notch is infinite in theory, but in practical circuits precision matched components will offer -60db of suppression while ordinary components can offer -40 to -50db of suppression.

V. RESULTS AND DISCUSSIONS

The op-amp circuit is designed by using Carbon Nano Tube Field Effect Transistor (CNTFET) and it is simulated with H-Spice. The filter circuits such as low pass filter, high pass filter, band pass filter and band reject filter are designed using CNTFET based op-amp circuits and simulated using H-Spice. The simulated results are presented and discussed in this section.

A. Low Pass Filter

The frequency response of the designed Low pass filter is shown in Figure 7. Since the CNTFET opamp is designed with improved frequency response, low-pass filter designd using such opamp provides maximum passband flatness and sharp transition from passband to stopband.

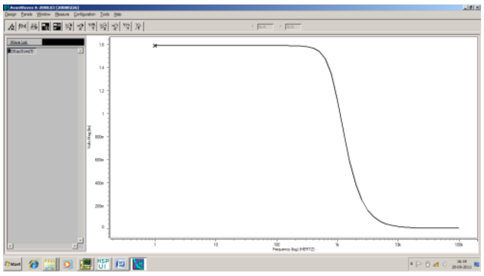

Figure 7: Frequency response of Low Pass Filter

B. High Pass Filter

Since the CNTFET opamp used for designing this high pass filter posses improved frequency response, it provides maximum passband flatness and sharp transition from passband to stopband in similar shape to a low-pass, just inverted in frequency as shown in Figure 8. For the high-pass filter, the gain for low frequencies could be approximated by the ratio of the resistor values used. The gain for the high frequencies could also be approximated just by varying the ratio of the capacitor values used.

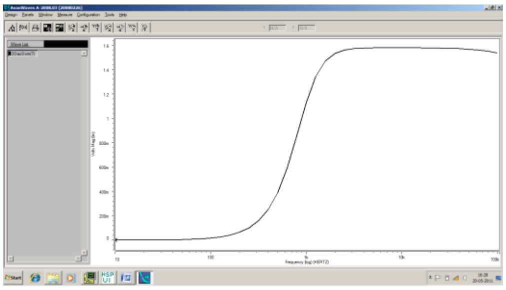

Figure 8: Frequency response of High Pass Filter

C. Band Pass Filter

The frequency response of Band Pass filter is shown in Figure 9. The CNTFET op amp slew rate is sufficient to allow the waveform at the center frequency to swing to the amplitude required.

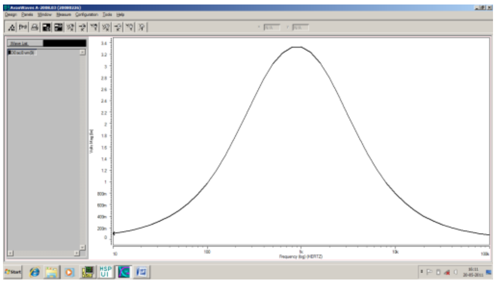

Figure 9: Frequency response of Band Pass Filter

D. Band Reject Filter

The frequency response of Band Reject filter is shown in Figure 10.

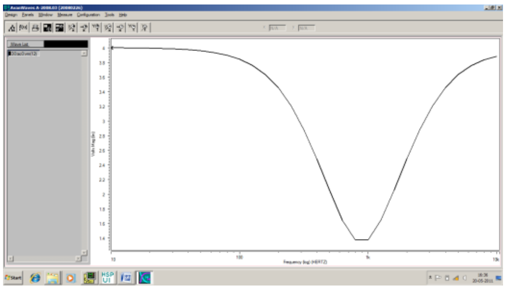

Figure 10: Frequency response of Band Reject Filter

VI. CONCLUSION

We present a circuit compatible model of the MOSFET like single walled Carbon Nanotube Field Effect Transistors (CNTFETs). CNTFET Opamp circuit is designed with improved current voltage limiting and phase/frequency response extensions. The CNTFET opamp has been used for designing various active filters such as low pass filter, high pass filter, band pass filter, band reject filter etc and simulated using Hspice. The simulated results are showing better performance than the MOSFET opamp circuits. It is shown from the frequency response characteristics of various filters that the filtering can be performed successfully over the designed range with a reasonable accuracy.

REFERENCES

[1] Arijit Raychowdhury, Saibal Mukhopadhyay and Kaushik Roy, " Modeling of Ballistic Carbon Nanotube Field Effect Transistors for Efficient Circuit Simulation", *ICCAD'03,*pp.487- 490, November 11-13, 2003.

[2] H.-S. P. Wong, "Beyond the Conventional Transistor," IBM J. Research & Development, March/May, pp. 133-168, 2002.

[3] T. Skotnicki, J. A. Hutchby, T.-J. King, H.-S. P. Wong, F. Beouff, "The Road to the End of CMOS Scaling," IEEE Circuits and Devices Magazine, pp. 16 – 26, 2005.

[4] Peng, N., H. Li and Q. Zhang, 2009. "Nano Scale contacts between carbon Nanotubes and metallic Pads," Acsnano, 10: 1016-25. 11.

[5] Tans, S., A. Verschaerea and C. Dekker, "Room temperature transistor based on a SWCN," Science, 397: 49-52, 1998.

[6] Martel, R., T. Schmidt, H. Shea and T. Avouris, "S-and M-WCNTFET Si transistors," Applied physics Letter, 73: 24 47-49, 1998.

[7] S. Heinze, J. Tersoff, R. Martel, V. Derycke, J.Appenzeller, and P.Avouris, "Carbon nanotubes as Schottky barrier transistors," Phys. Rev.Lett., vol. 89, no. 10, pp. 106 801-1–106 801-4, 2002.

[8] Fabien Pr´egaldiny et.al.,"Design Oriented Compact Models for CNTFETs", IEEE Trans. Elec.dev., 2006.

[9] A. Bahari, G. Arasteh and S. Taghizadeh, "Nanometer-Scaled Contacts in CNTFETs," World Applied Sciences Journal 7 (Supplement 1): 18-21, 2009

[10] J. Deng and H.-S P. Wong, "A Compact SPICE Model for Carbon Nanotube Field Effect Transistors Including Non-Idealities and Its Application — Part I: Model of the Intrinsic Channel Region," Submitted to *IEEE Transactions on Electron Devices*, 2007.

[11] J. Deng and H.-S P. Wong, "A Compact SPICE Model for Carbon Nanotube Field Effect Transistors Including Non-Idealities and Its Application — Part II: Full Device Model and Circuit Performance Benchmarking," Submitted to *IEEE Transactions on Electron Devices*, 2007.

[12] J. Chen, C. Klinke, A. Afzali, and P. Avouris, "Self-aligned carbon nanotube transistors with charge transfer doping," *Applied Physics Letters*, vol. 86, pp. 123108, 2005.

[13] A. Javey, J. Guo, M. Paulsson, Q. Wang, D. Mann, M. Lundstrom, and H. Dai, "High-Field Quasiballistic Transport in Short Carbon Nanotubes," *Physical Review Letters*, vo. 92, pp. 106804, 2004.

[14] J. Guo and M. Lundstrom, "Role of Phonon Scattering In Carbon Nanotube Field-Effect Transistors," *Applied Physics Letters*, vol. 86, pp. 193103, 2005.

[15] T. A. Fjeldly, T. Ytterdal, M. S. Shur, "Introduction to Device Modeling and Circuit Simulation," *Wiley-Interscience, New York*, 1998.

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