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Design of Cntfet Based Interfacing Circuits for On-Chip Cnt Interconnect

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Abstract: The design of CNTFET based transceiver is proposed for On-chip CNT interconnects. A CNTFET based transceiver is presented to reduce the complexity and improve the speed of operation and bandwidth of CNT interconnects. An input multiplexed CNTFET transmitter architecture with Current mode multiplexer and a high speed and wide bandwidth voltage mode CNTFET sense amplifier are proposed to achieve high speed of operation with low power dissipation. It offers the key advantages of low input impedance of current sense amplifier for channel termination results high data rate and variable common mode voltage does not need for current sensing receiver which leads to less design complexity of transmitter. The proposed CNTFET transceiver is studied through simulation with Synopsys HSPICE using 32nm technology models. The results obtained are compared with MOSFET based transceiver. Simulation results show that current CNTFET based transceiver exhibits 90% less delay and power dissipation compared to MOSFET based transceivers.

Key words: On-chip interconnects · 32nmtechnology · Copper(Cu) · Carbon Nanotube(CNT) · Single-walled CNT(SWCNT) · Carbon nanotube field effect transistor (CNTFET)

INTRODUCTION

As the VLSI technology continues to scale, increases the integrated circuit density and performance. Scaling shrinks the dimensions of transistors and interconnects. Initially, scaling shows performance improvement in transistors whereas it degrades the interconnect performance. Scaling of interconnect results more delay and power dissipation [1]. Various circuit level techniques were proposed to alleviate these problems in interconnect [2]. As the integrated circuit scales below 45nm, material level issues like source-drain tunneling, subthreshold leakage arises in MOS transistors. Besides, interconnect resistance increases due to electromigration and electroscattering [3]. This will force the researchers to find an alternate material for transistor as well as interconnect. A carbon nanotube (CNT) is proposed as an alternate material for both transistor and interconnect because it can be act as metal and semiconductor depending upon its chirality vector. By considering the indices (n, m) shown in Fig. 1, the nanotube is consider as metallic if n = m or n-m = 3i where i is an integer. Otherwise, the tube is semiconducting [4, 5]. Metallic CNT can be used as on-chip interconnect. CNT interconnect is proposed to replace the copper interconnect to alleviate the physical limitations are imposed by scaling on copper.

To transmit and receive the signal in interconnect, transceivers are used. In transceivers, transmitter and receiver should be highly sensitive, faster and have wide bandwidth to transmit and detect the signals through interconnects [6]. In this paper, current mode multiplexed input driver architecture is used to implement the transmitter [7]. It requires only one driver with less current. The output of transmission line is connected to

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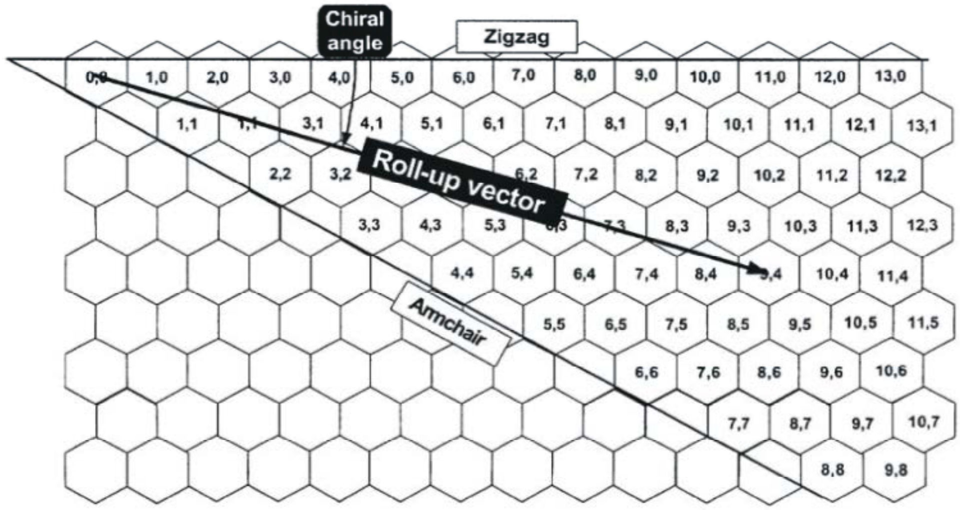

Fig. 1: Unrolled graphite sheet

input of transimpedance amplifier used as receiver. So it gives less loads to transmission line compared to the transceiver used in [6]. In this paper, transceivers, transmitter and receiver, are designed with CNTFET for CNT interconnects.

This paper is organized as follows: Section 2 presents the CNTFET and section 3 explains the proposed CNTFET transmitter and receiver. Section 4 shows the simulation results and section 5 presents the results and discussions. Section 6 concludes.

MATERIALS AND METHODS

Carbon Nanotube Field Effect Transistors (CNTFET): Carbon nanotube field effect transistors (CNTFET) are promising nano-scaled devices to implement the high performance, dense and low power circuits. A CNTFET cited to a FET that utilizes a single CNT or an array of CNT's as the channel material instead of bulk silicon in the traditional MOSFET structure.

CNTFETs are the FETs that utilize semiconducting CNTs as channel material between two metal electrodes that are act as a source and drain contacts [8]. The operation concept of CNTFET is similar to that of traditional silicon devices. As shown in Fig.2, this three terminal device consists of a semiconducting nanotube, acting as conducting channel that link the source and drain contacts. The device is turned ON or OFF electrostatically through the gate

The core of a CNTFET is a carbon nanotube. CNTFET is the most promising alternate for MOSFET because the operating principle and the device structure are similar to MOS devices and also the possibility of reusing the established CMOS design configurations. CNT has high current carrying ability in the order 10μA/nm^2. This is much higher as compared to standard metal wires which could carry 10nA/nm^2. CNTFETs can have almost a near-ballistic transport characteristic because the mean free path for electrons in SWCNTs exceed close to 1 μm. This will results higher speed device as compared to silicon MOSFETs. Carbon nanotubes are promising for the future Nano-electronics due to their superior electrical, mechanical and thermal properties. CNTFET has similar structure like MOSFET except that the silicon channel is replaced by carbon nanotubes. Improvements such as orientations and arrangements of the carbon nanotube have been constantly being research on so as to have a better end result [9].

CNTFET Transceiver Architecture: Transceivers ensure high speed for signal propagation through interconnect. It consists of transmitter, called driver, channel as interconnect and receiver, as shown in Fig. 3. Transmitters are used to convert the digital data into voltage or current signals and transmit it through the long interconnects. The transmitted signals through interconnect experience attenuation. Receivers, called sense amplifiers, sense and amplify the attenuated signal in interconnect and latched it to the next stage. In this paper, transceiver has designed with CNTFET for both voltage and current mode CNT interconnects [10,11].

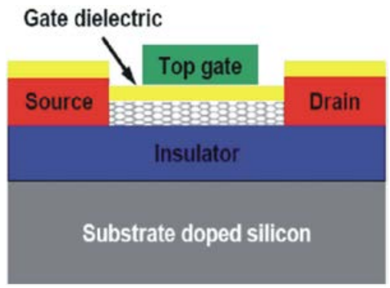

Fig. 2: Circuit for CNTFET

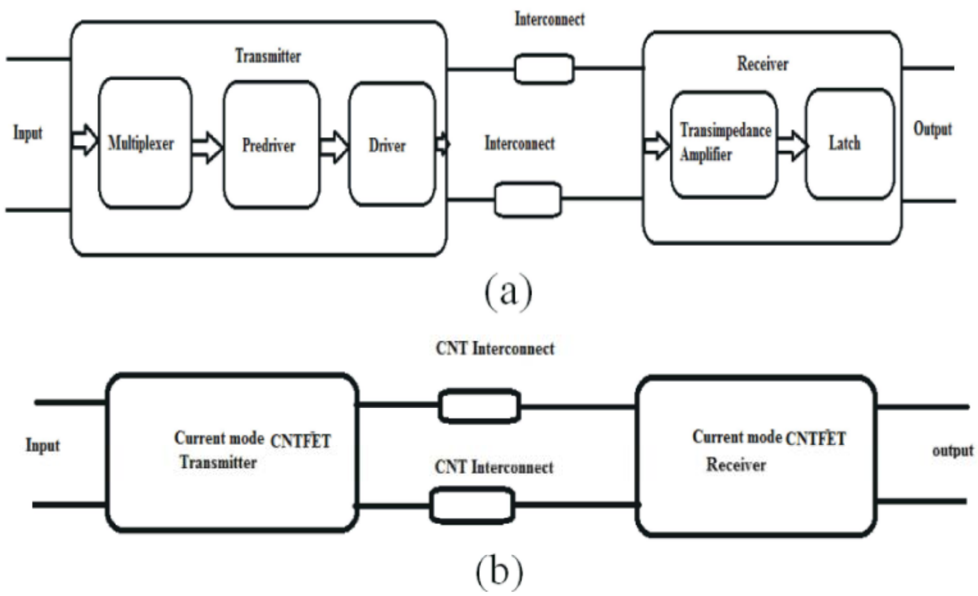

Fig. 3: Transceiver Architecture (a) Voltage mode (b) Current mode

Theory

CNTFET Interconnect Transmitter: The main function of serial link transmitter comprises serialization of parallel data and carries either voltage or current of sufficiently large amplitude. It provides impedance matching with interconnect impedance to minimize the reflection at the near end of the interconnect. Serialization is done by multiplexers. Multiplexers are implemented with pseudo NCNTFET to improve the speed of response. Chain of inverters is used as pre-driver. The output drivers are the voltage mode driver and current mode driver.

Voltage Mode CNTEFT Transmitter: The voltage mode transmitter converts the data into voltage signal, transmitted to interconnect. It consists of multiplexer, pre-driver and output driver. The transmitter multiplexes parallel data (D0-D3) and generates differential serial data output to drive the interconnect segment. Pseudo NCNTFET based voltage mode multiplexer [6] requires only one driver for all the inputs. The output depends on the selection line and input data. Pre-driver is used to convert full swing signal into limited swing signal, thus the output delay reduces. Finally, the output driver further reduces the signal swing and thus reduces the power consumption. The complement signal is generated similarly by using the complemented data inputs to output.

Current Mode CNTFET Transmitter: In current mode CNTFET transmitter, digital data is converted into current signal which is transmitted through interconnect. It uses a new on-chip signaling method that relies on the differential current mode signaling to improve both delay and power dissipation compared to voltage mode CNTFET transmitter []. This proposed method can be used for point-to-point as well as N-to-1 connections. It does not require any pre-driver and driver like in voltage mode transmitter; hence it alleviates the area and delay

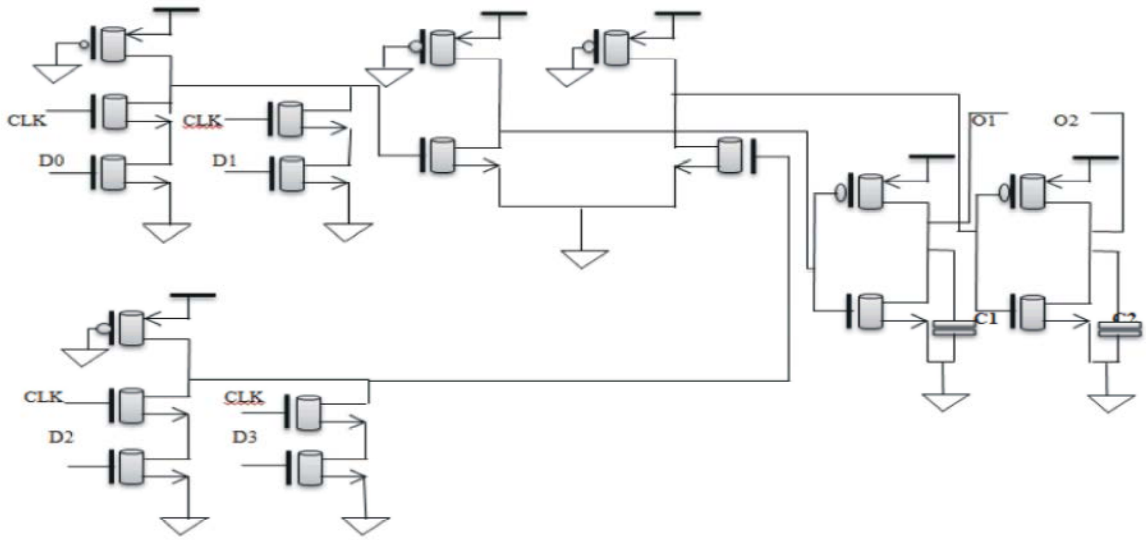

Fig. 4: Voltage mode CNTFET bd traasensmitter

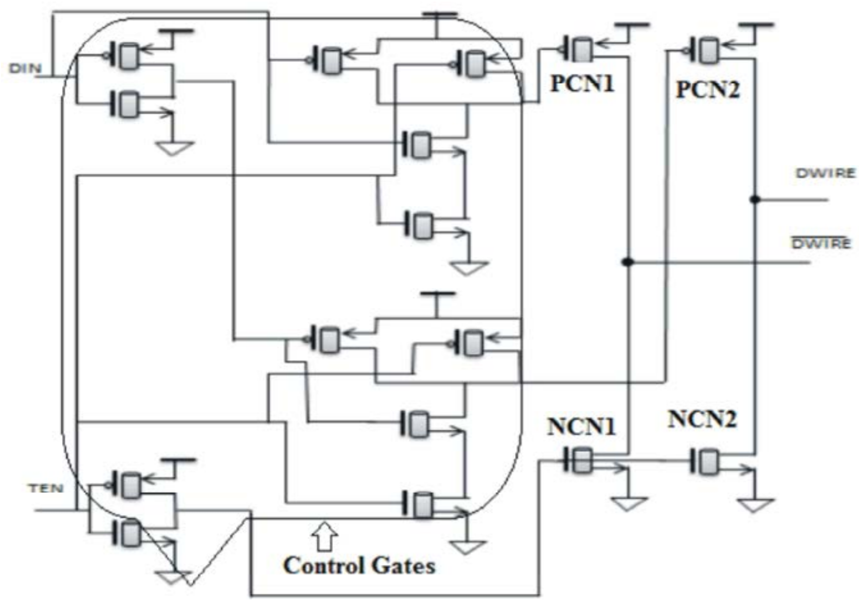

Fig. 5: Current mode Single PCNTFET (SPCNF) transmitter

overhead in voltage mode transmitters for signal propagation. In this circuit, transmitter generates the differential current at the output. The current mode transmitter contains two current sources (PCN1, PCN2) and control gates. Signal TEN (Transmit Enable) controls the transmitter operation and enables the transmitter to charge and discharge interconnects. When TEN is HIGH, one of the PCNTFET in the transmitter is active depends on DIN and transmits the current signal through interconnect. As DIN is High, PCN2 is ON; current is transmitted through dwire. When DIN is Low, PCN1 is ON, current is drawn in dwire' and not in dwire. Input DIN must be stable as long as the transmitter is enabled. When TEN is LOW, NCNTFETs (NCN1, NCN2) are turned ON and discharge interconnects through them. It initiates the transmitter for next data transfer.

CNTFET Interconnect Receiver: The digital data is recovered from the propagated voltage waveform by two operations: sampling the input waveform at the correct instant and determine the digital value of the sampled voltage. The signal is transmitted from transmitter to receiver through interconnect. Interconnect is terminated with a termination resistor (R_t) at the receiving end to avoid reflection. Voltage across R_t acts as input for the receiver. Sense amplifiers are used as receivers [6]. Initially, sense amplifiers were used in memories to detect bitline voltages whereas in interconnects, it is used to receive signal from it. They are classified into voltage mode sense amplifier receiver and current mode sense amplifier receiver depending on the type of input variable it have. Both voltage and current mode receivers are implemented with MOSFET for copper interconnect [13, 14]

CNTFET Based Receiver: Conventional gate isolated voltage mode sense amplifier [15], implemented with CNTFET, is used as a receiver for CNT interconnect. It exhibits less delay and power dissipation compared to MOSFET based receivers. CNTFET current mode sense amplifier is used to detect the signal from current mode CNT interconnect. It does not require extra termination resistor like voltage mode receiver.

Voltage Mode CNTFET Receiver: The digital data is recovered from the propagated voltage signal by the CNTFET based voltage mode receiver shown in Fig. 6. Differential amplifier front end is used to receive the attenuated signal from interconnect and convert it into a valid voltage levels at the output by regeneration action of cross coupled inverters. Transistors M1-M2 form the differential input stage. Transistors M3-M6 form the cross coupled inverter. M7 and M8 are the pre-charge transistors, used to pre-charge the output to VDD. M10 is equalization transistor which is used to reduce the aperture time of sense amplifier. The aperture time is the minimum time taken by the circuit to sample the input to produce correct output. When CLK is low, outputs are pre-charged to high voltage level. It does not affected by input. When CLK is high, inputs start to influence the output. Initially both the outputs are tried to discharge but one of the output is faster than other depends upon the input. There is a small difference between two outputs and then it will activate the regenerative action of cross coupled inverter. This action makes one output high and the other one is low according to inputs.

Current Mode CNTFET Receiver: It consists of a common gate configuration as an input stage, a pair of cross coupled inverters as shown in Fig. 7. Common gate configuration has low input impedance, which minimizes the charging and discharging times of the capacitance at the input node of sense amplifier which in turn leads to less delay. This low input impedance acts as the termination resistor in the transmission line model of interconnects.

Transistors M1 and M2 form the low impedance front end stage. Transistors M3-M6 forms the cross coupled inverter pair. M7 & M8, M9 & M10 are pre-charge and isolation transistors. Isolation transistors are used to isolate the inputs from the sensing nodes of cross coupled inverters during the falling edge of the clock.

The operation of the circuit is as follows: On the falling edge of the clock, outputs are pre-charged to VDD through M7 & M8. M9 & M10 are switched OFF to isolate the inputs from the sensing nodes. During the rising edge of the clock M9 & M10 are turned ON, which connects the inputs to the sensing nodes. Both output nodes start to discharge but one is faster than the other. Regenerative action takes place in the cross coupled inverters, when a small difference exists between the two outputs. One output reaches LOW, while the other output reaches HIGH.

Simulation Results: Simulations are carried out at 32nm technology by using Synopsys HSPICE and Avanwaves waveform viewer. The CNT interconnect is modeled as RLC equivalent circuit in HSPICE. The transmitter and receiver circuits are implemented with Stanford CNTFET model and BSIM4 model for MOSFET in 32nm technology. The simulation results are presented in below. The existing MOSFET based voltage mode transmitter and receiver architectures are implemented with CNTFET [16]. A novel architecture is proposed for current mode transmitter and receiver, simulated with both CNTFET and MOSFET and made a performance comparison between them.

Simulation Results of CNTFET Transmitter: The output waveforms of voltage and current mode CNTFET transmitters o btained through simulation are shown in Fig. 8 (a) and (b). Fig. 8 (a) shows that output waveforms of voltage mode transmitter, where D0 to D3 are input data signals. Out1 and Out2 are true and complement output signals. The average power and delay are measured from HSPICE simulation are 480.2µW and 32.2pS. Fig. 8b shows the output waveforms of SPCNF transmitter. Din and TEN are the input and control signals and Dwire and Dwire' are the true and complement output currents. The observed average power and delay from simulation are 51.7 µW and 1.68pS.

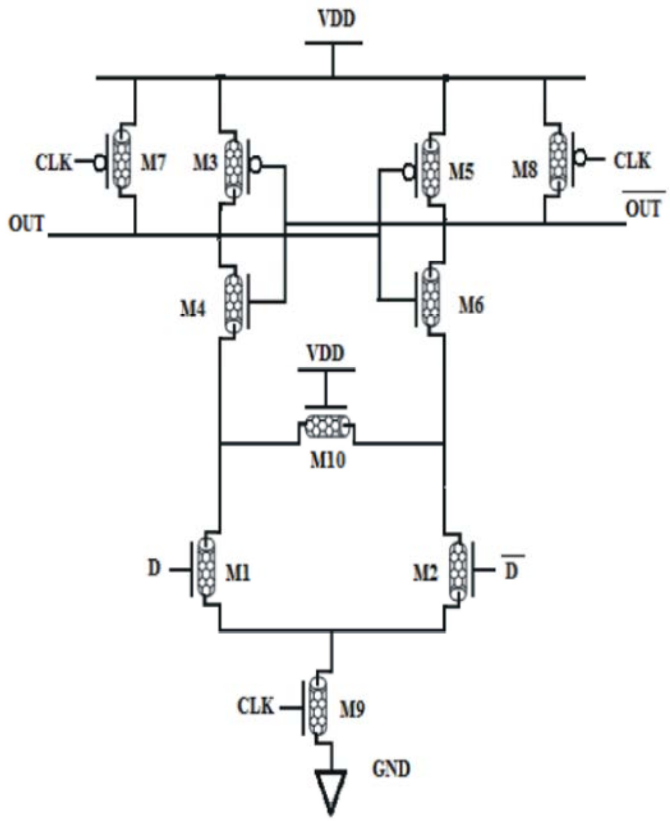

Fig. 6: Voltage mode interconnect receiver

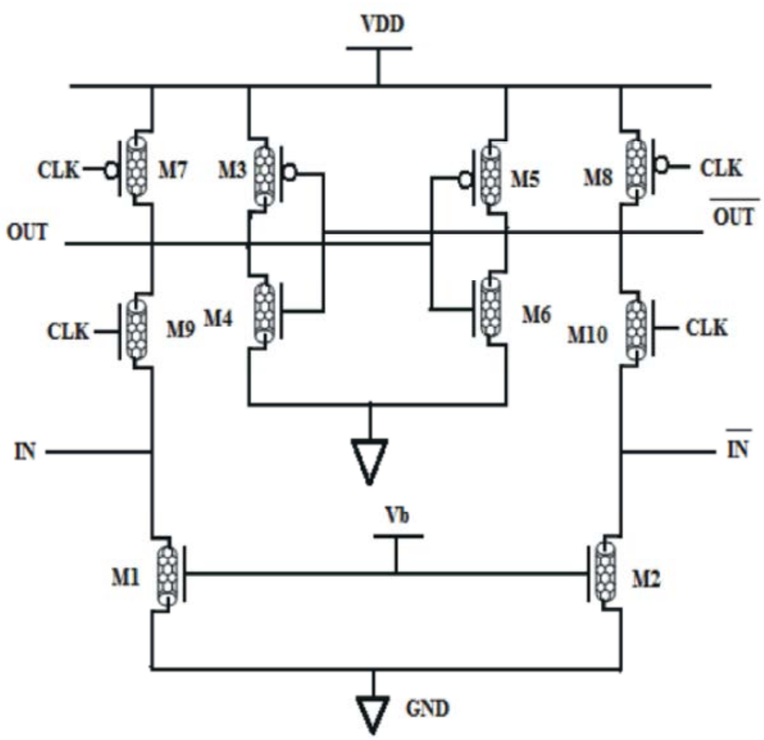

Fig. 7: Current mode interconnect receiver

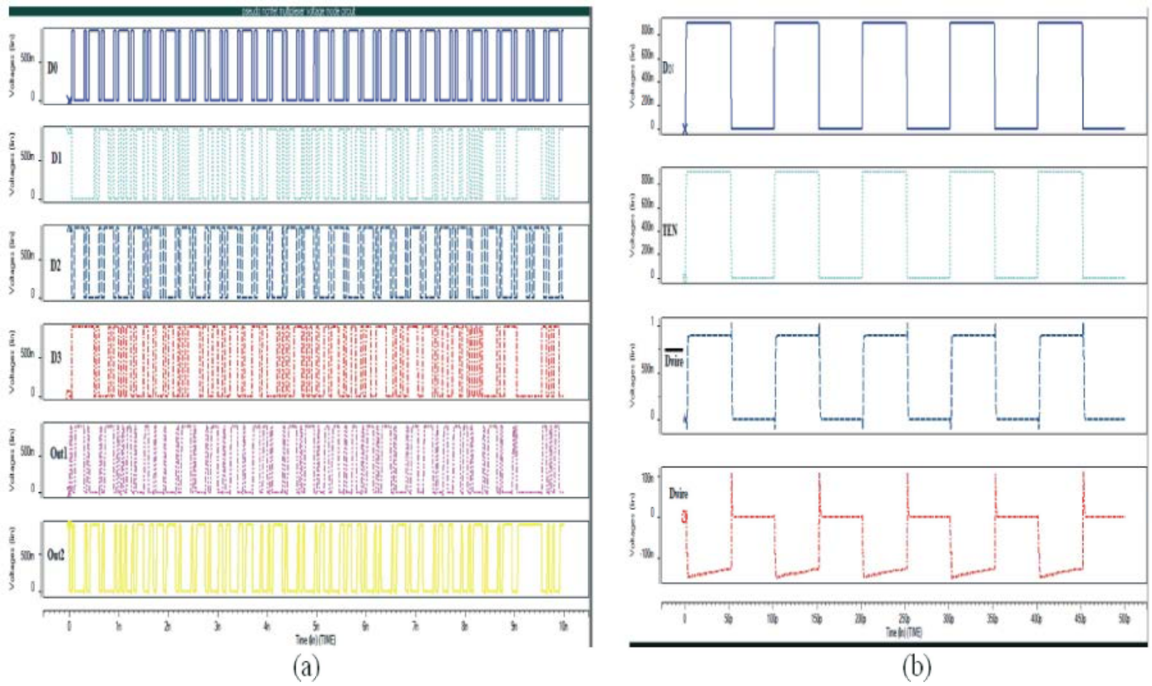

Fig. 8: Output Waveforms of CNTFET Transmitter (a) Voltage Mode (b) Current Mode

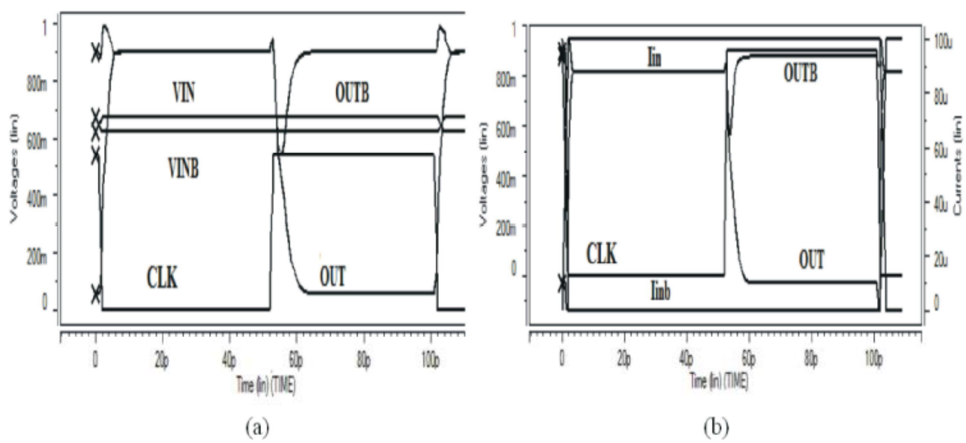

Fig. 9: Transient response time waveforms of interconnect receiver. (a)Voltage mode (b) Current mode

Simulation Results of CNTFET Receiver: The response time plot of voltage mode and current mode receivers are shown in Fig. 9 (a) and (b). Fig. 9a, shows the clock (CLK), input (IN, VINB) and output (OUT, OUTB) voltage waveforms of voltage mode sense amplifiers. Fig. 9b shows the clock (CLK), input currents (Iin, Iinb) and output (OUT, OUTB) voltage waveforms of current mode sense amplifier. From time response plots, the response time of voltage mode receiver is 3.1ps to produce differential output and CNCISA generate the responses 1.5ps respectively. Current sensing receivers take less time to respond to its inputs compared to voltage sensing because it has only two transistors in the evaluation path and has two discharge paths to ground. Hence, it takes less time response compared to conventional architecture.

RESULTS AND DISCUSSION

The performance metrics obtained from simulation is summarised in Table 1. The performance of CNTFET transceiver and CNT interconnect are compared against MOSFET based transceiver and copper interconnect.the detailed discussion about performance comparison is given below.

Table 1: Performance comparison of MOSFET and CNTFET transceivers at 32nm technology

			Performance Metrics		
			Delay (pS)	Power (μW)	PDP (fJ)
Transmitter	VOLTAGE	MOSFET	140	525	78.0
	MODE	CNTFET	32.2	480	15.5
	CURRENT	MOSFET	36.6	4760	174
	MODE	CNTFET	1.68	51.7	0.0869
Receiver	VOLTAGE	MOSFET	33	50.0	1.650
	MODE	CNTFET	3.3	47.77	0.155
	CURRENT	MOSFET	7.33	1.04	0.00766
	MODE	CNTFET	1.5	0.0056	0.006
Interconnect (10mm Length)	VOLTAGE	Copper	21700	92.2	2000
	MODE	CNT	110	0.452	0.04972
	CURRENT	Copper	293	67	19.631
	MODE	CNT	8.54	0.00347	0.000029
Total interconnect Link	VOLTAGE	Copper	21783	667	14529
	MODE	CNT	175.02	582.22	101.85
	CURRENT	Copper	336.9	4828	1626.55
	MODE	CNT	11.6	51.7	0.5916

Transmitter: In transmitter, both voltage and current mode, CNTFET exhibit less delay and power dissipation compared to the MOSFET because of ballistic transport of carbon nanotube, large mean free path and remote joule heating effect.In MOSFET based transmitters, current mode exhibit less delay for signal propagation whereas dissipate more power compared to voltage mode. In CNTFET based transmitters, Current mode exibit 22 times less delay and 93 times less power dissipation compared to MOSFET due to high current carrying capacity of CNT and the current mode signaling avoids the charging and discharging of interconnect capacitance.

Receiver: In receiver, CNTFET reveals better performance both in voltage mode and current mode when compared MOSFET. CNTFET based receiver with current mode signaling is power efficient by the factor of 1000 compared to its MOSFET counterpart because the current sensing circuit does not dissipate dynamic power and also CNT dissipate power remotely [17].

Interconnect: Copper interconnect produces enormous delay for signal propagation and also dissipates more power due to increase in resistance while scaling the internnect. CNT interconnect with current mode cieperforming better than copper eventhough the technolgy scales below 32nm technology because of ballistic transport, large mean free path and high current carrying capability of CNT.

Interconnect Link: The total interconnect link consists of transmitter , receiver and interconnect. The total delay and power of an interconnect link are sum of the delay and power of transmitter, receiver and interconnect. From table I, it is observed that copper interconnect link with voltage mode exhibit more delay and less power dissipation compared to current mode copper interconnect link whreaas in CNT interconnect link, current mode signaling achieves less delay and power dissipation compared to voltage mode signaling.

CONCLUSION AND FUTURE WORK

The design of CNTFET based transceiver has proposed for on-chip CNT interconnect. CNTFET based transmitter and receiver shows excellent speed and power performance compared to MOSFET based transceiver. Based on the performance comparisons shown in table I, it is observed that current mode CNT shows better delay and power performance as transistor and interconnect compared to MOSFET and copper interconnect. Copper interconnect with currentmode signaling dissipates more power compared to voltage mode whereas CNT with current mode dissipates very less power in transistor as well as in interconnect because of its high current carrying capability , ballistic transport property and remote joule heating effect. Hence it is concluded that current mode CNT can be used as interconnect and transistor in future IC to achieve Thz speed with low power dissipation.

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