N-Type Carbon-Nanotube MOSFET Device Profile Optimization for Very Large Scale Integration

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Carbon-nanotube metal oxide semiconductor field effect transistor (CN-MOSFET) is a promising future device candidate. The electrical characteristics of 16 nm N-type CN-MOSFETs are explored in this paper. The optimum N-type CN-MOSFET device profiles with different number of tubes are identified for achieving the highest on-state to off-state current ratio (I_{on}/I_{off}). The influence of substrate voltage on device performance is also investigated in this paper. Tradeoffs between subthreshold leakage current and overall switch quality are evaluated with different substrate bias voltages. Technology development guidelines for achieving high-speed, low-leakage, area efficient, and manufacturable carbon nanotube integrated circuits are provided.

Keywords: Carbon nanotube array, Lower subthreshold leakage, Higher performance, Substrate bias, Charge screening effect

1. INTRODUCTION

As the complementary metal-oxide semiconductor (CMOS) technology progresses into the 22 nm regime, the fundamental limitations of silicon are felt stronger. New superior materials are needed to achieve higher performance and scalable CMOS integrated circuits in the future. Carbon-nanotube (CN) transistor is a promising candidate for replacing silicon metal oxide semiconductor field effect transistor (Si-MOSFET) [1-6]. CN transistors display desirable characteristics such as elastic carrier scattering, ballistic carrier transport, and smaller device footprint (area) as compared to conventional Si-MOSFETs [1].

Two types of CN transistors have recently attracted significant attention in the literature: Schottky Barrier (SB) controlled switch (CN-SBFET) and MOSFET-like switch (CN-MOSFET) [1-6]. CN-SBFETs are formed by directly attaching the intrinsic nanotube channels to the metal source/drain contacts. CN-SBFETs show ambipolar carrier transport. Alternatively, the CN-MOSFET displays unipolar behavior with heavily doped source and drain extension regions. A coaxial gated CN-SBFET and a CN-MOSFET are compared in [2]. CN-MOSFETs produce higher on-state and lower leakage currents. By providing a significantly higher I_{on}/I_{off} ratio, CN-MOSFETs display better scalability as compared to CN-

SBFETs. CN-MOSFET is the focus of the study presented in this paper due to the superior performance as compared to the CN-SBFET.

The structure of a planar-gated N-type CN-MOSFET is shown in Fig. 1. The CNs are heavily doped with donors (n^+) in the source and drain extension regions in an N-type CN-MOSFET. The nanotubes are undoped under the gate. The cross-sectional view of a CN-MOSFET is shown in Fig. 2. Multiple nanotubes are placed in parallel to form an array that produces sufficient current with a CN-MOSFET.

Inspired by the developments in CN related research, publications on novel circuit techniques for very large scale integration (VLSI) of CN-MOSFETs have recently started to appear in literature [7-11]. All of these studies are based on Stanford CN-MOSFET HSPICE compact model [12]. A multi-threshold voltage six-transistor (6-T) static random access memory (SRAM) cell using CN-MOSFETs is presented by Lin et al. in [7] to provide higher performance as compared to the 32 nm-Si-MOSFET based memory cells. The characteristics of 6-T CN-MOSFET and Si-MOSFET SRAM cells are compared by Moradinassab et al. in [8] assuming a 32 nm CMOS technology. A new CN-MOSFET SRAM cell is proposed by Ebrahimi and Afzali-Kusha in [9] to enhance the read static noise margin as compared to a conventional Si-MOSFET memory cell. A novel eight-transistor CN-MOSFET SRAM cell is proposed by Kim et al. in [10] to lower the dynamic switching power consumption

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Fig. 1. Three-dimensional view of a planar-gated N-type CN-MOSFET.

Fig. 2. Cross-sectional view of a multi-tube CN-MOSFET. W_{ov} is the overhang of the gate from the edge of CN array.

as compared to silicon FinFET memory circuits. A new ternary inverter is proposed by Lin *et al.* in [11] for lower power consumption and higher performance with the CN-MOSFET technology. The conclusions of these recent publications are however difficult to reproduce and verify. Unlike a Si-MOSFET, device size is not determined merely by the physical gate width and channel length in a CN-MOSFET. The complex relationship between device sizing and performance due to the unique material properties and nanotube array structure of a CN-MOSFET is typically overlooked in these previous publications. Device and circuit design options such as transistor sizing (number of tubes), carbon nanotube array physical structure (nanotube diameters and pitch), and choice of substrate voltage are not discussed in sufficient detail.

A thorough understanding and a careful optimization of the device structure are essential to be able to develop high-performance integrated circuits with CN transistors. A p-channel CN-MOSFET device profile optimization study for achieving high-speed carbon nanotube integrated circuits is presented in [13]. Alternatively, the electrical characteristics of 16 nm N-type CN-MOSFETs are explored from a circuit designer's point of view in this paper. The purpose of this paper is to bridge the fledgling CN-MOSFET based novel circuit development and VLSI efforts to the underlying emerging CN technology. The optimization study is based on the Stanford CN-MOSFET HSPICE compact model [12]. The dependence of device performance on the physical geometry of carbon nanotubes is presented. The optimum high-performance device profiles that provide the maximum I_{on}/I_{off} ratio are identified. Technology development and utilization guidelines are provided to achieve high-speed, low-leakage, area efficient, and manufacturable integrated circuits with CN field effect transistors.

The paper is organized as follows. The performance-critical parameters in the physical structure of a CN-MOSFET are highlighted in Section 2. The optimization results with technology development and utilization guidelines for high-performance 16 nm N-type CN-MOSFETs are presented in Section 3. Finally, some conclusions are offered in Section 4.

Fig. 3. The structure of a carbon nanotube with chirality vector C_h (n, m). The carbon nanotube is formed by rolling up a sheet of graphene along the chirality vector C_h . The carbon to carbon inter-atomic distance along the hexagonal lattice is $b \approx 1.44 \text{ \AA}$. The lattice unit vector is characterized by (a_1, a_2) . The inter-atomic distances along the lattice unit vectors are $a = |a_1| = |a_2| = \sqrt{3}b = 2.49 \text{ \AA}$. $C_h = n \cdot a_1 + m \cdot a_2$.

2. IMPORTANT CN-MOSFET PARAMETERS

Important device parameters for modeling and performance characterization of CN-MOSFETs are highlighted in this section. The relationships among CN diameter, energy bandgap, I_{on} , and I_{off} in a CN-MOSFET are explained in Section 2.1. The distinctions among the physical gate width, physical channel width, and effective channel width in a CN-MOSFET are described in Section 2.2. The important set of physical parameters from the 16 nm CN-MOSFET technology considered in this performance optimization study is presented in Section 2.3.

2.1 Carbon-nanotube diameter

The diameter of a single-walled CN (SWCN) is specified by the chirality vector C_h (n, m) as shown in Fig. 3. Both n and m are positive integers. SWCN is metallic if $|n - m|$ is an integer multiple of 3 [14]. Alternatively, if $|n - m|$ is not an integer multiple of 3, SWCN is a semiconductor [14]. The diameter (d_{CN}) of a single-walled CN (SWCN) with chirality vector (n, m) is [14]

$$d_{CN} = \frac{a \sqrt{n^2 + nm + m^2}}{\pi} \quad (1)$$

where a (2.49 Å) is the carbon to carbon inter-atomic distance along the lattice unit vectors a_1 and a_2 as shown in Fig. 3.

The energy bandgap (E_g) of carbon nanotube is inversely proportional to the nanotube diameter [14]. The diameter therefore influences both on-state and off-state currents. Appropriate choice of CN diameter is critical to achieve a high speed and energy efficient electrical switch.

2.2 Width of a CN-MOSFET

The channel is a doped single piece of silicon extending between the source and drain terminals in a Si-MOSFET. The gate width is essentially the length of the (polysilicon or metal) gate that overlaps the channel area perpendicular to the direction of current flow between the source and drain in a Si-MOSFET. The definition and measurement of the gate width are however different in a CN-MOSFET. Unlike a Si-MOSFET, the channel of a CN-MOSFET is composed of an array of discrete nanotubes

Table 1. Set of process parameters for 16 nm N-type CN-MOSFET.

Process parameters	Default values for 32 nm CN-MOSFET [12]	Fixed values for 16 nm CN-MOSFET
Supply voltage	0.9 V	0.7 V
Physical channel length (L_g)	32 nm	16 nm
Length of doped CN source-side (L_s)	32 nm	16 nm
Length of doped CN drain-side (L_d)	32 nm	16 nm
Dielectric constant of bottom gate (K_{sub})	SiO ₂ (4)	SiO ₂ (4)
Thick oxide	10 μ m	10 μ m
Top gate dielectric material (High- K_{ox})	HfO ₂ (16)	ZrO ₂ (25)
Thickness of top gate dielectric (T_{ox})	4 nm	3 nm
Height of gate/source/drain contact	64 nm	60 nm
Flatband voltage of N-type CN-MOSFET (V_{fb})	0	0
Fermi level of n ⁺ doped source/drain CN region (E_{fn})	0.6 eV (~0.8%) (uniformly distributed)	0.6 eV (~0.8%) (uniformly distributed)
Mean free path: intrinsic CN	200 nm	200 nm
Mean free path: doped CN	15 nm	15 nm
Interconnect capacitance	0.213 fF/ μ m	0.3 fF/ μ m ^a

^aInterconnect capacitance is estimated assuming a gate/source/drain contact height of 60 nm and a contact spacing of 16 nm.

separated by insulator as illustrated in Fig. 2. The gate width of a CN-MOSFET can be therefore defined in three different ways.

The total area of a CN-MOSFET is determined by the physical gate width (W_g) as shown in Fig. 2. W_g is determined by the intertube pitch, the number of tubes, the diameter of CNs, and the gate overhangs beyond the carbon nanotubes at the two ends of the channel. W_g is

$$W_g = s * (N - 1) + d_{CN} + 2 * W_{ov} \quad (2)$$

where N is the number of tubes in a CN-MOSFET. Inter-tube pitch (s) is the distance between the centers of two adjacent nanotubes that form the channel of a CN-MOSFET. W_{ov} is the overhang width of the gate from the edge of the CN array as shown in Fig. 2. W_{ov} helps to lower the probability of leaving uncovered carbon nanotubes in the channel area due to the misalignments of the gate during fabrication. In a Si-MOSFET, the overhang width of the gate from the edge of the active region is typically 2λ [15]. Assuming a similar photolithographic manufacturing process for CN transistors, W_{ov} at each end is assumed to be 2λ (16 nm) in this study as shown in Fig. 2.

A single CN typically provides a limited amount of current. An array of multiple nanotubes is therefore necessary to be able to produce sufficient drain-to-source current in a CN-MOSFET. The physical channel width (W_{ch}) is the total accumulated diameters of the nanotubes that form the channel in a CN-MOSFET. W_{ch} is

$$W_{ch} = N * d_{CN} \quad (3)$$

The electric field lines emerging from the gate terminal terminate on the CNs that form the channel. These electric field lines penetrating into the channel area are screened by the neighboring insulated nanotubes. When a positive voltage is applied on the gate terminal of an N-type CN-MOSFET, the charge induced on the CNs interact as illustrated in Fig. 4. The gate-to-channel capacitance and the resulting current produced by a nanotube are reduced due to enhanced screening effect with decreased inter-tube spacing (pitch). Charge screening reduces the effective width of the channel, thereby degrading the device current [16, 17]. Considering the charge screening effect, the effective channel width (W_{eff}) of a CN-MOSFET is

$$W_{eff} = N * d_{CN} * \alpha \quad (4)$$

where α is the screening effect coefficient ($0 < \alpha \leq 1$). When there is only one tube per gate, $\alpha = 1$. For $N > 1$, α is primarily

Fig. 4. The charge screening effect in an N-type multi-tube CN-MOSFET. A positive voltage is applied to the gate. (a) The channel contains only one nanotube. (b) The channel contains multiple tubes ($N = 3$) with large inter-tube pitch s_1 . (c) The channel contains multiple tubes ($N = 3$) with a smaller inter-tube pitch s_2 . As the pitch is reduced ($s_2 < s_1$), electric field lines are screened and shielded by neighboring tubes, thereby lowering the screening effect coefficient (α) and the effective channel width (W_{eff}).

determined by the nanotube pitch. Screening effect is also influenced by the CN diameter, the number of tubes, the supply voltage, and the channel length of the device.

The current produced by a CN-MOSFET is determined by the effective channel width W_{eff} . W_{eff} depends on the intensity of the electrical interactions among the carbon nanotubes that form the channel. Alternatively, the physical gate width W_g depends only on the physical geometry of the device. W_g and W_{eff} are therefore different in a CN-MOSFET. Unlike a Si-MOSFET, W_g contributes only to the parasitic capacitance and physical transistor area without directly influencing the drain current pro-

duced by a CN-MOSFET.

2.3 Device scaling and parameter settings

The fixed (not considered for optimization) process parameters of the 16nm CN-MOSFETs in this study are listed in Table 1. The 'Default value for 32 nm CN-MOSFET' column includes the default device parameters of the 32 nm Stanford University CN-MOSFET technology presented in [12]. As listed in Table 1, the interconnect capacitance increases when the channel length is scaled [16]. High-performance nanotube transistors with integrated high-k (~25) dielectrics (zirconium oxide thin-films) are described by Javey *et al.* in [18]. A high-k gate oxide material (ZrO_2) with a dielectric constant of 25 and a nominal thickness of 3 nm is assumed here to achieve high-speed transistors.

3. OPTIMIZATION OF N-TYPE CN-MOSFET

The current produced by a CN-MOSFET depends on important physical parameters such as the diameters of nanotubes, the inter-tube pitch, and the number of tubes. These parameters determine the effective channel width and device strength. In this section, the CN diameters are optimized to maximize the $I_{\text{on}}/I_{\text{off}}$ ratio for different nanotube arrays with different effective device channel widths. The influence of inter-tube pitch on device performance is evaluated with two different substrate (bottom-gate) voltages. The design tradeoffs among I_{on} , I_{off} , and $I_{\text{on}}/I_{\text{off}}$ for N-type CN-MOSFETs are presented. All of the nanotubes are assumed to be semiconducting with uniform inter-tube pitch. Imperfections such as diameter variations and metallic nanotubes during the manufacturing of CN-MOSFETs are not considered in this paper. The die temperature is assumed to be 90°C [20]. The nominal supply voltage is 0.7 V. The channel lengths of all the CN-MOSFETs considered in this paper are 16 nm ($L_g = 16$ nm).

3.1 Nanotube diameter optimization

In this section, the diameter of carbon nanotubes is optimized to achieve the maximum $I_{\text{on}}/I_{\text{off}}$ ratio. I_{on} is the drain current at $V_{\text{GS}} = V_{\text{DS}} = V_{\text{DD}} = 0.7$ V. I_{off} is the subthreshold leakage current at $V_{\text{GS}} = 0$ V and $V_{\text{DS}} = V_{\text{DD}} = 0.7$ V.

In order to evaluate the dependence of I_{on} and I_{off} on the diameter of nanotubes, an N-type CN-MOSFET with 2 tubes is presented as an example next. As discussed in Section 2.2, nanotube array pitch has a strong influence on I_{on} produced by a CN-MOSFET. Similarly, the maximum achievable $I_{\text{on}}/I_{\text{off}}$ is affected by the array pitch. The optimum nanotube diameter that maximizes $I_{\text{on}}/I_{\text{off}}$ however is insensitive to the nanotube array pitch. The inter-tube pitch (s) is assumed to be 1 μm in this section to effectively eliminate the charge screening effect (i.e., $\alpha \approx 1$) and determine the maximum $I_{\text{on}}/I_{\text{off}}$ achievable with a CN-MOSFET. The maximum performance provided by an ideal CN transistor that does not suffer from charge screening effect is identified. The range of nanotube diameters is from 0.5 nm to 3 nm. All the possible chirality vectors (n, m) that can produce the diameters in this range are considered in this study.

For a fixed number of tubes and a fixed pitch, enlarging the CN diameter enhances both I_{on} and I_{off} as shown in Fig. 5. The increased diameter decreases the resistance of the channel region. The source and drain resistances are also reduced due to the higher number of carriers induced in the semiconducting sub-bands as the diameter is enlarged. The variation of I_{on} is primarily

Fig. 5. The variation of I_{on} , I_{off} , and $I_{\text{on}}/I_{\text{off}}$ with diameter for $N = 2$. The substrate voltage ($V_{\text{sub}} = 0$ V).

due to the strong modulation of the source and drain resistances with the CN diameter [21].

Subthreshold leakage current is exponentially increased with the diameter. I_{off} is controlled by the energy bandgap (E_g) of CNs. I_{off} is dominated by the band-to-band tunneling current in a CN-MOSFET [2]. The energy bandgap of CN is reduced as the diameter is increased. In the subthreshold region, particularly when a negative gate voltage is applied to an N-type CN-MOSFET, the band-to-band tunneling current is enhanced with increased diameter. The additional band-to-band leakage current (I_{btt}) through the semiconducting sub-bands is particularly severe for high V_{DS} in a CN-MOSFET [21].

When the diameter (d_{CN}) is increased, I_{on} and I_{off} are enhanced at different rates. The $I_{\text{on}}/I_{\text{off}}$ is therefore maximized at an optimum diameter ($d_{\text{OPT},0\text{V}}$) as shown in Figs. 5 and 6 with 0V substrate bias. Similar trends for the variation of I_{on} , I_{off} , and $I_{\text{on}}/I_{\text{off}}$ with the diameter are observed when the substrate is connected to the power supply (0.7 V) as shown in Fig. 6. The x-axis of Fig. 6 corresponds to I_{on} when the diameter is increased from 0.5 nm to 3 nm.

The substrate can be viewed as a second (bottom) gate below a thick oxide layer in a CN-MOSFET [12]. I_{on} is enhanced due to stronger channel inversion with a higher substrate voltage. The subthreshold leakage current however is also increased when the substrate voltage is higher than 0 V. An n-channel CN-MOSFET cannot be effectively cut-off provided that the substrate is connected to the power supply ($V_{\text{sub}} = V_{\text{DD}} = 0.7$ V). The maximum achievable $I_{\text{on}}/I_{\text{off}}$ and the corresponding optimum nanotube diameter are therefore reduced with a higher substrate voltage.

The variation of maximum achievable $I_{\text{on}}/I_{\text{off}}$ with the number of tubes ($1 \leq N \leq 35$) for two different substrate voltages is shown in Fig. 7. For each number of tubes, the percent enhancement of the maximum achievable $I_{\text{on}}/I_{\text{off}}$ by decreasing the substrate voltage from 0.7 V to 0 V is also shown. By connecting the substrate to the ground, the maximum $I_{\text{on}}/I_{\text{off}}$ is enhanced by up to 43% as compared to the maximum $I_{\text{on}}/I_{\text{off}}$ achievable with a higher substrate voltage.

3.2 The effect of substrate voltage on the optimum diameter

The variation of optimum nanotube diameter with the transistor size (number of tubes) for $V_{\text{sub}} = 0$ V and $V_{\text{sub}} = 0.7$ V is shown in Fig. 8. Both $d_{\text{OPT},0\text{V}}$ and $d_{\text{OPT},0.7\text{V}}$ are reduced with the increased N as shown in Fig. 8. When N is increased from 1 to 35, $d_{\text{OPT},0.7\text{V}}$ is reduced from 0.872 nm to 0.691 nm (a reduction of approximately 26%). Alternatively, when $V_{\text{sub}} = 0$ V, $d_{\text{OPT},0\text{V}}$ is reduced from

Fig. 6. The variations of I_{off} and $I_{\text{on}}/I_{\text{off}}$ with I_{on} for two different substrate voltages (0 V and 0.7 V). $N = 2$.

0.993 nm to 0.804 nm (a reduction of approximately 23%) with the increased transistor size (as N is increased from 1 to 35).

In addition to enhanced $I_{\text{on}}/I_{\text{off}}$, the optimum nanotube diameter that maximizes $I_{\text{on}}/I_{\text{off}}$ is also enlarged with a smaller substrate voltage. For $1 \leq N \leq 35$, $d_{\text{OPT}_0\text{V}}$ is 7.4% to 16.4% larger as compared to $d_{\text{OPT}_0.7\text{V}}$ as shown in Fig. 8. A lower substrate voltage with a larger optimum diameter may be preferable for easier manufacturability. Furthermore, the increased $d_{\text{OPT}_0\text{V}}$ has little influence on the device physical gate width (W_g) and area. W_g is typically dominated by the gate overhang width, the nanorarray pitch, and the number of nanotubes in a CN-MOSFET.

3.3 Device performance versus integration density tradeoffs

The ideal maximum $I_{\text{on}}/I_{\text{off}}$ of an optimized N-type CN-MOSFET is achieved at a high inter-tube pitch (assumed to be 1 μm in Section 3.1) where the screening effect is negligible. This pitch is however impractically long from an area efficiency point of view. Shorter pitches are desirable to enhance the integration density of a chip with CN-MOSFET technology. In this section, the effect of pitch reduction on the maximum achievable $I_{\text{on}}/I_{\text{off}}$ is evaluated.

As shown in Fig. 9 with $N = 2$, the optimum diameter d_{OPT} is independent of the inter-tube pitch (s). The optimum diameters are maintained similar to the values illustrated in Fig. 8 when the pitch is scaled for various transistor sizes ($1 \leq N \leq 35$). As listed in Tables 2 and 3, for each N , four (relatively more practical from an area efficiency point of view) pitch values (s) and the corresponding physical gate widths (W_g) are identified with two different substrate voltages. 5%, 10%, 15%, and 20% degradations from the ideal maximum $I_{\text{on}}/I_{\text{off}}$ (that could only be achieved by an essentially ideal switch with an impractically large pitch and negligible charge screening effect) are assumed to be acceptable for implementing high performance and compact integrated circuits.

As N is increased from 1 to 35, both optimum $I_{\text{on}}/I_{\text{off}}$ and W_g are increased. For a fixed N , shorter s is desirable for a smaller device area (W_g is reduced). However, the effective channel width (W_{eff}) is also reduced due to the enhanced charge screening effect (lower a) with a shorter nanotube pitch (see Eq. (4)). The I_{on} therefore decreases with a shorter s . The variation of the subthreshold leakage current with the pitch is negligible since I_{off} is primarily controlled by the E_g and I_{btbt} . Lowering the pitch to reduce the device area degrades $I_{\text{on}}/I_{\text{off}}$ as listed in Tables

Fig. 7. The variations of maximum achievable $I_{\text{on}}/I_{\text{off}}$ with the number of tubes for two different substrate voltages (0 V and 0.7 V). The percent enhancement of maximum achievable $I_{\text{on}}/I_{\text{off}}$ by lowering the substrate bias voltage from 0.7 V to 0 V is also shown.

Fig. 8. The variation of optimum diameter with transistor size (number of tubes) for two different substrate voltages (0 V and 0.7 V).

2 and 3. There is therefore a tradeoff between switch performance ($I_{\text{on}}/I_{\text{off}}$) and area efficiency (W_g). Alternatively, as listed in Tables 2 and 3 and as discussed in Section 3.1, for the same number of tubes and similar physical gate width, the maximum achievable $I_{\text{on}}/I_{\text{off}}$ is enhanced with $V_{\text{sub}} = 0$ V as compared to $V_{\text{sub}} = 0.7$ V. A smaller substrate voltage is therefore desirable to enhance $I_{\text{on}}/I_{\text{off}}$ without degrading the integration density of n-channel CN-MOSFETs.

3.4 Uniform nanotube diameter for manufacturability with different transistor sizes

As shown in Sections 3.1 and 3.2, $I_{\text{on}}/I_{\text{off}}$ can be maximized by manufacturing nanotubes with carefully optimized diameters d_{OPT} for achieving high-speed and low-power integrated circuits. Billions of transistors with various driving strengths (various device widths) will be required to implement complex state-of-the-art integrated circuits with the carbon nanotube technology. The strength of CN-MOSFETs can be tuned by adjusting the number of tubes that form the channel as explained in Section 2. The optimum diameters are listed in Tables 2 and 3 for various sizes of N-type CN-MOSFETs with different numbers of tubes ($1 \leq N \leq 35$).

The optimum diameter for achieving the maximum $I_{\text{on}}/I_{\text{off}}$ varies with the number of tubes (transistor size) as shown in Fig. 8.

Table 2. Pitch values for 5%, 10%, 15%, and 20% degradation from the maximum achievable I_{ON}/I_{OFF} with 16 nm N-type CN-MOSFETs. $T = 90^\circ\text{C}$. Substrate voltage = 0 V.

Number of tubes (N) ^a	Optimum diameter $d_{OPT,0V}$ (nm)	Optimum chirality vector (n, m)	Maximum I_{on}/I_{off} ($\times 10^6$) at $s = 1 \mu\text{m}$	With 5% degradation from maximum I_{on}/I_{off}		With 10% degradation from maximum I_{on}/I_{off}		With 15% degradation from maximum I_{on}/I_{off}		With 20% degradation from maximum I_{on}/I_{off}	
				s (nm)	W_g (nm)	s (nm)	W_g (nm)	s (nm)	W_g (nm)	s (nm)	W_g (nm)
1	0.993	(1, 12), (12, 1)	0.913	--	32.99	--	32.99	--	32.99	--	32.99
2	0.934	(3, 10), (10, 3)	1.530	10.64	43.57	7.05	39.98	5.35	38.28	4.27	37.20
6	0.883	(2, 10), (10, 2)	3.327	14.09	103.33	9.64	81.08	7.6	70.88	6.32	64.48
10	0.872	(0, 11), (11, 0)	4.688	14.65	164.72	10.05	123.32	7.94	104.33	6.64	92.63
14	0.839	(4, 8), (8, 4)	5.896	14.81	225.37	10.17	165.05	8.04	137.36	6.72	120.20
18	0.839	(4, 8), (8, 4)	6.949	14.94	286.82	10.27	207.43	8.12	170.88	6.8	148.44
22	0.828	(5, 7), (7, 5)	7.919	14.98	347.41	10.29	248.92	8.14	203.77	6.82	176.05
26	0.828	(5, 7), (7, 5)	8.766	15.04	408.83	10.34	291.33	8.18	237.33	6.85	204.08
30	0.804	(2, 9), (9, 2)	9.598	14.96	466.64	10.28	330.92	8.13	268.57	6.82	230.58
35	0.804	(2, 9), (9, 2)	10.600	15.01	543.14	10.31	383.34	8.16	310.24	6.84	265.36

^aAll the device sizes for $1 \leq N \leq 35$ are considered in this optimization study. Only a small number of selected devices are listed in the table due to limited space.

Table 3. Pitch values for 5%, 10%, 15%, and 20% degradation from the maximum achievable I_{ON}/I_{OFF} with 16 nm N-type CN-MOSFETs. $T = 90^\circ\text{C}$. Substrate voltage = 0.7 V.

Number of tubes (N) ^a	Optimum diameter $d_{OPT,0.7V}$ (nm)	Optimum chirality vector (n, m)	Maximum I_{on}/I_{off} ($\times 10^6$) at $s = 1 \mu\text{m}$	With 5% degradation from maximum I_{on}/I_{off}		With 10% degradation from maximum I_{on}/I_{off}		With 15% degradation from maximum I_{on}/I_{off}		With 20% degradation from maximum I_{on}/I_{off}	
				s (nm)	W_g (nm)	s (nm)	W_g (nm)	s (nm)	W_g (nm)	s (nm)	W_g (nm)
1	0.872	(0, 11), (11, 0)	0.789	--	32.87	--	32.87	--	32.87	--	32.87
2	0.828	(5, 7), (7, 5)	1.319	11.06	43.89	7.4	40.23	5.7	38.53	5.42	38.25
6	0.781	(3, 8), (8, 3)	2.705	14.7	106.28	10.17	83.63	8.12	73.38	6.86	67.08
10	0.781	(3, 8), (8, 3)	3.646	16.77	183.71	11.64	137.54	9.31	116.57	7.89	103.79
14	0.756	(1, 9), (9, 1)	4.388	16.06	241.54	11.15	177.71	8.92	148.72	7.56	131.04
18	0.756	(5, 6), (6, 5)	5.022	16.95	320.91	11.78	233.02	9.42	192.90	7.99	168.59
22	0.705	(3, 7), (7, 3)	5.536	13.14	308.65	9.10	223.81	7.28	185.59	6.17	162.28
26	0.705	(3, 7), (7, 3)	6.252	13.69	374.96	9.49	269.96	7.59	222.46	6.44	193.71
30	0.705	(3, 7), (7, 3)	6.906	14.17	443.64	9.82	317.49	7.86	260.65	6.67	226.14
35	0.691	(4, 6), (6, 4)	7.702	13.47	490.67	9.34	350.25	7.46	286.33	6.33	247.91

^aAll the device sizes for $1 \leq N \leq 35$ are considered in this optimization study. Only a small number of selected devices are listed in the table due to limited space.

Fabricating nanotubes with different diameters for various sizes of CN-MOSFETs on a complex chip is not practical. For low-cost and high-yield manufacturability, it is highly desirable to have only one uniform nanotube diameter (for a single- V_{th} CN-MOSFET technology) across a chip. The effect of a uniform diameter on the performance of various sizes of CN-MOSFETs is evaluated in this section. 35 different transistor sizes are considered (the number of tubes is varied from 1 to 35) to determine a single uniform and manufacturable diameter with acceptable degradation from the ideal switch performance.

Three possible uniform diameters are evaluated for various sizes of CN-MOSFETs. The average diameter (d_{AVG}) is the average value of the optimum nanotube diameters shown in Fig. 8 for $1 \leq N \leq 35$. The maximum diameter (d_{MAX}) is the maximum d_{OPT} determined for $1 \leq N \leq 35$. Alternatively, the minimum diameter (d_{MIN}) is the minimum d_{OPT} in Fig. 8 for $1 \leq N \leq 35$. The d_{MAX} and d_{MIN} are observed for $N = 1$ and $N = 35$, respectively, since d_{OPT} that maximizes I_{on}/I_{off} is reduced with increased N as illustrated in Fig. 8.

The degradation from the ideal maximum I_{on}/I_{off} (observed at $d_{OPT,0V}$) for $d_{AVG,0V}$, $d_{MAX,0V}$, and $d_{MIN,0V}$ with different transistor sizes is shown in Fig. 10 when $V_{sub} = 0$ V. By using nanotubes

with a uniform diameter of $d_{AVG,0V}$ (0.839 nm), the degradation from the ideal maximum I_{on}/I_{off} is maintained below 20% for $3 \leq N \leq 35$. Further analysis for even larger transistors reveals that I_{on}/I_{off} degradations are maintained below the 20% demarcation line by employing a uniform diameter of 0.839 nm for $36 \leq N \leq 73$ as well. For a single- V_{th} CN transistor technology where only one uniform nanotube diameter is desirable for low-cost and high-yield manufacturability, the suggested nanotube diameter is therefore 0.839 nm for n-channel CN-MOSFETs with $V_{sub} = 0$ V. For $N < 3$, a diameter larger than $d_{AVG,0V}$ is desirable for higher I_{on}/I_{off} . Alternatively, for $N > 73$, a diameter smaller than $d_{AVG,0V}$ is desirable to limit I_{on}/I_{off} degradations to less than 20%.

Similar analysis is also conducted to determine a practical uniform diameter for which the I_{on}/I_{off} degradations are smaller than 20% at $V_{sub} = 0.7$ V. As shown in Fig. 11, the performance degradations are maintained below 20% by using nanotubes with a uniform diameter of $d_{AVG,0.7V}$ (0.756 nm) for $3 \leq N \leq 43$. Therefore, the suggested uniform nanotube diameter is 0.756 nm for $V_{sub} = 0.7$ V. For $N < 3$, a diameter larger than $d_{AVG,0.7V}$ is desirable for higher I_{on}/I_{off} . Alternatively, for $N > 43$, a diameter smaller than $d_{AVG,0.7V}$ is desirable to maintain I_{on}/I_{off} degradations below 20%.

Fig. 9. The variation of I_{on}/I_{off} with the diameter for different pitch values (s). The optimum diameter that maximizes I_{on}/I_{off} is insensitive to pitch variations. The substrate voltage = 0 V.

Fig. 10. The degradation from the ideal maximum I_{on}/I_{off} (observed at $d_{OPT,0V}$) for $d_{AVG,0V}$, $d_{MAX,0V}$, and $d_{MIN,0V}$ with different number of tubes when the substrate voltage = 0 V. The 20% degradation from the ideal maximum I_{on}/I_{off} is demarcated with a dashed line. The performance degradations of devices below the demarcation line are less than 20% as compared to the ideal maximum I_{on}/I_{off} values at $V_{sub} = 0$ V.

4. CONCLUSIONS

The influence of device physical parameters on the electrical characteristics of 16 nm N-type CN-MOSFETs is explored in this paper. The optimum 16 nm device profiles are identified for different nanotube arrays at 90°C. Design guidelines are provided for the development and accurate characterization of high-speed, low-power, and compact integrated circuits with carbon-nanotube transistors.

The nanotube diameter, the inter-tube pitch, and the number of tubes per device play the most important roles in determining both the area (the physical gate width) and the performance (I_{on}/I_{off}) of carbon-nanotube transistors. Tradeoffs among area efficiency, I_{on} , and I_{on}/I_{off} of N-type CN-MOSFETs are explored in this paper. Furthermore, the influence of substrate voltage on device performance is investigated. For a higher number of tubes (larger transistor size), the optimum diameter that maximizes I_{on}/I_{off} is reduced. For a manufacturable, high-yield, and low-cost integrated circuit however only one uniform nanotube diameter

Fig. 11. The degradation from the ideal maximum I_{on}/I_{off} (observed at $d_{OPT,0.7V}$) for $d_{AVG,0.7V}$, $d_{MAX,0.7V}$, and $d_{MIN,0.7V}$ with different number of tubes when the substrate voltage = 0.7 V. The 20% degradation from the ideal maximum I_{on}/I_{off} is demarcated with a dashed line. The performance degradations of devices below the demarcation line are less than 20% as compared to the ideal maximum I_{on}/I_{off} values at $V_{sub} = 0.7$ V.

is desirable across a chip. The degradation from the maximum achievable I_{on}/I_{off} is maintained below 20% with a uniform diameter of 0.839 nm for $3 \leq N \leq 73$ when the substrate is connected to the ground. Alternatively, if the substrate is connected to the power supply, the suggested uniform nanotube diameter for high-performance and manufacturability is 0.756 nm for $3 \leq N \leq 43$.

Either increasing the diameter beyond the optimum or increasing the substrate voltage of an N-type CN-MOSFET enhances the I_{on} . This speed enhancement is however achieved at the cost of higher leakage current and degraded I_{on}/I_{off} . The I_{on}/I_{off} can be enhanced by increasing the pitch (weakening the charge screening effect). A larger pitch however degrades the integration density. The tradeoffs between I_{on}/I_{off} and area efficiency are highlighted with this study. Practical pitch values for achieving high performance within 5%, 10%, 15%, and 20% of an ideal switch are identified.

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