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Theoretical Architecture and Fabrication Techniques of Carbon Nanotube Field-Effect Transistors

Niuniu Zhang

Department of Microelectronic Science and Engineering, Guilin University of Electronic Technology, Guilin, China
aruki0530@gmail.com

Abstract. Silicon-based transistors face scaling limits from short-channel effects, power crises, and rising costs. Carbon nanotube field-effect transistors (CNTFETs), exploiting quasi-ballistic transport and one-dimensional electrostatics of single-walled carbon nanotubes (SWCNTs), offer superior short-channel control and high performance at sub-20 nm scales. This paper examines recent advances in CNTFET theory and fabrication, covering device principles, structures, chirality-dependent properties, carrier injection, and electrostatic metrics compared to silicon FinFETs. Manufacturing progress includes chirality-selective synthesis, wafer-scale alignment, ultralow-resistance contacts, high-κ/metal gate integration, and low-damage processes. Comparative analysis reveals that CNTFETs achieve drain-induced barrier lowering (DIBL) and sub-threshold swing (SS) surpassing their silicon counterparts, highlighting their promise for scalable, high-performance post-silicon electronics.

Keywords: CNTFETs, device physics, carrier transport, silicon-based transistors

1. Introduction

The relentless miniaturization of silicon-based metal–oxide–semiconductor field-effect transistors (MOSFETs) is confronting intrinsic physical constraints as well as escalating manufacturing costs. When the gate length is reduced below 20 nm, short-channel effects (SCEs)—including threshold voltage roll-off, DIBL, and deterioration of SS—begin to degrade switching behavior markedly. At the same time, higher leakage currents contribute to substantial static power losses. The growing complexity of advanced lithography and patterning further raises questions about the long-term feasibility of Moore's law. In light of these challenges, one-dimensional channel materials such as SWCNTs have emerged as strong candidates for post-silicon technologies. Their near-ballistic carrier transport, atomically smooth surfaces, and adjustable band gaps provide clear advantages in electrostatic control, carrier mobility, and scaling potential over conventional silicon. Indeed, CNTFETs offer much higher carrier mobility (up to ~10^5 cm²/V·s) and superior gate electrostatic control due to their quasi-one-dimensional structure, enabling quasi-ballistic transport with long mean free paths [1]. During the past decade, research into CNTFETs has advanced from proof-of-concept devices—capable of delivering high on-current densities and sub-thermionic SS (even below 60 mV/dec)—to more sophisticated prototypes with improved yield and integration. For

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example, early CNTFETs with integrated ohmic contacts and high-κ dielectrics achieved SS around 70–80 mV/dec and high ON currents; band-to-band tunneling (TB-CNTFET) devices have demonstrated sub-60 mV/dec performance even at room temperature [2,3]. However, early devices were hindered by issues such as the coexistence of metallic and semiconducting nanotubes (chirality variation), substantial contact resistance, and imprecise channel placement. Chirality control and purity remain major challenges, limiting yield and uniformity [4]. Contact engineering has shown progress: optimized contact metals and larger band-gap CNTs significantly reduced contact resistance, improving the on/off ratio by orders of magnitude and aligning with roadmap targets [5]. While several reviews have discussed CNTFET synthesis techniques and fundamental operating principles, there is still a lack of integrated evaluations that, within the most recent years, connect theoretical device architectures with fabrication strategies. In particular, few studies have systematically correlated chirality-selective growth, contact interface engineering, and high-κ/metal gate-stack design with quantitative short-channel performance indicators like DIBL and SS.

In this paper, a targeted review of CNTFET device concepts and manufacturing methodologies. The discussion begins with the core operational mechanisms, structural configurations, chirality-dependent electronic characteristics, and electrostatic scaling properties of CNTFETs. This is followed by an examination of recent technological advances, including high-purity chirality-controlled synthesis, wafer-scale nanotube alignment, ultralow-resistance contact fabrication, high-κ/metal gate integration, and fabrication flows optimized to minimize structural damage. Where applicable, performance metrics are compared with those of cutting-edge silicon FinFETs to highlight both competitive advantages and persisting challenges. By integrating perspectives from theory and process technology, this review aims to clarify the decisive factors for CNTFET scalability and to inform strategies for their eventual commercialization.

2. Fundamental structure and working principles of CNTFETs

2.1. Basic working principle

Carbon nanotube field-effect transistors utilize the distinct semiconducting characteristics of SWCNTs as the channel material. Upon application of a gate voltage, this potential either modifies Schottky barriers at source/drain contacts or induces an inversion channel along the nanotube structure [6]. In contrast to conventional MOSFETs, charge carriers (electrons/holes) transport through the one-dimensional channel exhibits quasi-ballistic behavior with significantly suppressed scattering mechanisms. Conductance modulation stems from two primary mechanisms: field-effect-induced alterations in the nanotube's electronic band structure, which alter the density of states and energy alignment across the channel, and quantum-mechanical tunneling across the Schottky barrier formed at the metal-nanotube contacts, which facilitates carrier injection even under non-ideal barrier conditions. Ambipolar conduction commonly occurs due to symmetry in electron/hole injection barriers, though strategic doping or contact engineering enables unipolar functionality [7].

2.2. Device structure

Contemporary CNTFET designs implement two dominant architectures: top-gated and gate-all-around (GAA) configurations. The GAA geometry provides superior electrostatic control through complete encirclement of 8-15 nm diameter nanotube channels with high-κ gate dielectrics (e.g., HfO_2, Al_2O_3) coupled with metallic gates [8, 9]. Precise work function matching to nanotube band structures necessitates careful contact metal selection (palladium [Pd], scandium [Sc], and

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molybdenum [Mo]). Recent research has demonstrated two performance-enhancing device configurations: one employs suspended nanotube channels to suppress phonon scattering, while the other adopts substrate-shielded designs to alleviate dielectric disorder effects, both of which contribute to improved carrier transport and overall device performance [10].

2.3. π-Conjugated structures and chirality dependency

The electronic properties of SWCNTs are determined by the chiral indices (n, m), which are two integers defining how a graphene sheet is rolled up to form the nanotube. These indices dictate the atomic structure, diameter, and electronic characteristics of the nanotube, including the magnitude of the bandgap (E_g) and the effective mass of charge carriers. When n = m, the resulting armchair (n, n) nanotube is intrinsically metallic with $E_g = 0$. In contrast, (n, 0) configurations are referred to as zigzag, while those with both n and m nonzero and unequal are termed chiral nanotubes. Experimental and theoretical studies indicate that, except for armchair types, most SWCNTs—including zigzag and chiral structures—exhibit semiconducting behavior, with the bandgap approximately inversely proportional to the tube diameter, following the empirical relation $Eg \approx 0.8/d_{tube}(eV)$ [11]. However, as-synthesized CNT samples typically contain about 33% metallic nanotubes, which can significantly disrupt the desired semiconducting performance. In CNTFET fabrication, current chirality separation and selection strategies include precision sorting via density-gradient ultracentrifugation [12], selective deposition using DNA wrapping or templating, electrical breakdown to remove metallic pathways, and the integration of laterally aligned multi-tube arrays to ensure statistical uniformity [13].

2.4. Carrier injection and extraction

Efficient carrier injection in carbon nanotube field-effect transistors critically depends on achieving low Schottky barrier heights (SBH) at metal-SWCNT junctions. To realize such low-barrier contacts, metals like palladium (Pd) for p-type operation and scandium (Sc) for n-type behavior can form near-Ohmic interfaces under optimized fabrication conditions. Previous studies indicate that the contact between CNTs and metals is largely unaffected by Fermi-level pinning, enabling polarity control through work function engineering—using high-work-function Pd for p-type and low-work-function Sc for n-type conduction—although in many practical devices, Fermi-level pinning still imposes a constraint on minimizing contact resistance [14]. Beyond material selection, quantum transport simulations establish that the physical dimensions of contacts also govern injection efficiency. Specifically, optimized contact lengths must satisfy $Lc > \lambda$, where $\lambda \approx 15$ nm represents the carrier mean free path, ensuring carriers traverse the contact region without significant scattering [15]. These combined material and geometric optimizations directly manifest in device output characteristics: ballistically dominated devices achieve high-performance metrics, including saturation currents exceeding 25 μA/tube, while diffusive transport mechanisms degrade Ion/Ioff ratios due to increased scattering. Notably, recent advances in three-dimensional (3D) contact architectures enhance carrier injection area, suppressing contact resistance below 3kΩ·μm—a critical benchmark for scalable nanoelectronics [16].

2.5. Electrostatics and short-channel effects

As the gate length (Lg) of MOSFETs approaches the scale of depletion widths (~20 nm and below), electrostatic control by the gate electrode degrades significantly, leading to a series of short-channel

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effects (SCEs). These effects are characterized by threshold voltage (V_{th}) roll-off, DIBL, and the degradation of subthreshold swing (SS). In conventional silicon-based FinFETs, when the gate length Lg is less than 20 nm, the SCEs are further intensified because of the enhanced influence of drain/source electric fields in multi-dimensional transport. Carbon nanotubes offer inherent advantages against SCEs owing to their one-dimensional (1D) ballistic transport characteristics and natural compatibility with gate-all-around (GAA) architectures. The fundamental metric governing SCE severity is the electrostatic scaling length (λ) [17]:

$$\lambda \propto \sqrt{\frac{\epsilon_{CNT} t_{ox} d_{CNT}}{\epsilon_{ox}}} \tag{1}$$

Where ϵ_{CNT} and ϵ_{ox} are the dielectric constants of the CNT channel and gate oxide, respectively, denotes oxide thickness, and represents the nanotube diameter. The atomic-scale confinement (< 2 nm) typical of CNTs reduces λ compared to planar Si devices. This reduction fundamentally enhances electrostatic gate control and mitigates SCEs at aggressively scaled dimensions [18].

2.6. Key performance metrics for SCE characterization

2.6.1. Drain-Induced Barrier Lowering (DIBL)

Physical Significance: DIBL quantifies the undesirable modulation of the source-channel potential barrier by the drain voltage (V_{ds}), resulting in threshold voltage reduction at high Vds. Higher DIBL indicates degraded gate control. When it comes to quantification, DIBL is calculated using the formula [19]:

$$\mathrm{DIBL} = \frac{\Delta V_{th}}{\Delta V_{ds}} = \frac{V_{th,low}\,V_{ds} - V_{th,high}\,V_{ds}}{V_{ds,high} - V_{ds,low}} \tag{2}$$

Here, $V_{th,\ low\ Vds}$, and $V_{th,\ high\ Vds}$ are the threshold voltages measured at low (e.g., 0.05 V) and high (e.g., 0.7-1.0 V) drain biases, respectively. In terms of the SCE benchmark, DIBL values exceedingly approximately 100 mV/V signify severe short-channel effects (SCE) issues. Experimentally, carbon nanotube field-effect transistors (CNTFETs) demonstrate superior immunity to SCE. For instance, in top-gated CNT FETs with gate lengths as short as 15 nm, DIBL values have been demonstrated to be as low as ~20 mV/V, showcasing exceptional short-channel control and near-ideal electrostatic behavior [20]. In sharp contrast, silicon FinFETs of similar gate lengths often exhibit DIBL values exceeding 150 mV/V, primarily due to less effective field screening. This stark difference is mainly attributed to the one-dimensional electrostatics of carbon nanotubes, which effectively suppress drain field penetration and short-channel effects.

2.6.2. Subthreshold Swing (SS)

Physical Significance: SS measures the efficiency of channel switching via gate voltage (V_{gs}), defined as the voltage required to reduce the drain current (I_{ds}) by one decade in the sub-threshold region. When it comes to Definition [21]:

$$\mathrm{SS} = \left(\frac{1}{\frac{d(I_{ds} log_{10})}{dV_{gs}}}\right) \tag{3}$$

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Fundamental Limit: The Boltzmann limit at room temperature imposes a minimum SS of ~60 mV/dec. CNTFETs inherently approach this limit due to their one-dimensional density of states. For example, top-gated CNTFETs with gate lengths of ~15 nm has demonstrated nearly ideal SS values of ~65 mV/dec, with modeling suggesting that further scaling to ~10 nm could maintain near-ideal behavior [20]. In contrast, advanced Si FinFETs—such as strained SiGe/Si super-lattice devices-commonly show SS values exceeding 80 mV/dec at comparable technology nodes due to short-channel effects and parasitic capacitances [22]. Gate-all-around (GAA)-like CNT architectures with optimized high-κ gate dielectrics have further demonstrated strong electrostatic control, achieving SS ≈ 65 mV/dec at sub-15 nm gate lengths [20].

2.6.3. Quantum Capacitance (CQ)

The quantum capacitance (CQ) originates from the finite density of electronic states near the Fermi level in low-dimensional systems such as CNTs. This phenomenon is particularly significant in both metallic and semiconducting CNTs due to the presence of one-dimensional (1D) Van Hove singularities in their density of states (DOS). The quantum capacitance can be expressed by the equation [23]:

$$C_Q = e^2 \cdot \mathrm{D}(E_F) \approx \frac{2e^2}{hV_F} \tag{4}$$

Where e represents the elementary charge, $D(E_F)$ is the DOS at the Fermi energy E_F, h is Planck's constant, and V_F is the Fermi velocity, which is approximately 8×10^5 m/s for CNTs. In the context of aggressively scaled devices, the total gate capacitance (C_G) is determined by the series combination of the geometric oxide capacitance (C_{OX}) and the quantum capacitance (C_Q), as described by the equation [24]:

$$\frac{1}{C_G} = \frac{1}{C_{OX}} + \frac{1}{C_Q} \tag{5}$$

For CNTs, the intrinsic one-dimensional electronic structure results in a relatively small unit-length quantum capacitance (C_Q). Experimental and modeling studies have shown that single-walled CNTs typically exhibit C_Q values in the range of approximately 50-100 aF μm^{-1}, depending on chirality and doping level [25]. As device scaling pushes the gate length (L_g) below ~20 nm with thinner gate dielectrics, C_Q can become comparable to the oxide capacitance (C_{OX}), making it a dominant factor that limits the overall gate capacitance [26]. When C_Q and C_{OX} are of the same order, the quantum-capacitance-dominated electrostatics strengthen gate control over the channel potential, thereby intrinsically suppressing DIBL and stabilizing the SS—effects that have been corroborated in recent C-V analysis and compact modeling for sub-20 nm CNTFETs [27].

3. The advanced manufacturing process of CNTFET

3.1. Synthesis and chirality control

High-purity (≥99.998%) semiconducting single-wall carbon nanotubes (s-SWCNTs)-the foundational material for high-performance CNTFETs are synthesized via aerosol Chemical Vapor Deposition (CVD) using cobalt/nickel catalysts at 900°C. To ensure compatibility with transistor applications, chirality-selective growth is critical: sulfur-based promoter modulation achieves >95% enrichment of (16,0) and (19,0) nanotubes, which exhibit ideal band gaps (~0.8-1.1 eV) for

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semiconductor channels in CNTFETs [28]. Further precision is enabled by flux-mediated cloning, which replicates specific (n, m) indices across wafers with<0.06 eV bandgap variation—essential for uniform threshold voltages in large-scale CNTFET arrays [29]. Post-synthesis, machine learning-assisted Raman spectroscopy screens metallic residuals (99.2% accuracy), eliminating conductive impurities that could degrade transistor off-state performance [30].

3.2. Precise positioning and directional arrangement

Advanced assembly techniques now enable precise alignment of carbon nanotubes (CNTs) on substrates. For highly oriented placement, dielectrophoresis (DEP) — when optimized for electrode geometry, frequency, and voltage amplitude — has been shown to produce extremely high orientation fidelity in CNT assemblies [31]. Applications demanding sub-2 nm resolution leverage DNA-origami templates, where sequence-specific binding and addressable binding sites provide single-molecule placement with near-nanometer (sub-to single-nm) spatial accuracy [32]. Large-area monolayer assembly approaches (liquid-interface and Langmuir-Blodgett variants) enable wafer-scale films with high directional uniformity and device-scale densities suitable for electronics integration [33]. To further enhance registry accuracy, area-selective and template-assisted ALD/chemical patterning methods achieve sub-10 nm site definition that can reduce placement errors to the few-nanometer regime [34]. Collectively, these methodologies establish foundations for wafer-scale integration of aligned CNT arrays, significantly enhancing carrier transport uniformity in fabricated devices.

3.3. Optimization of contact resistance

Table 1. Performance comparison of contact resistance optimization techniques

Method	Contact Material	R_c (kΩ·μm)	Technique
Hybrid Metalization [35]	Mo/WC	0.63	ALD nucleation + PVD fill ($\Phi_{Bp} \approx 0.08$ eV)
Phase-Change [36]	GeSbTe	0.41	Resistive switching interface
Van der Waals [37]	Pd/graphene	0.28	Barrier-free edge contact

As shown in Table 1, recent strategies for contact resistance optimization in CNTFETs employ diverse materials and interface engineering methods, achieving Rc values well below 1 kΩ·μm. An ultralow contact resistance on the order of tens of Ω·μm can be achieved by employing graphene edge-contact techniques, which effectively mitigate Fermi-level pinning through optimized sp^2 hybridization alignment [38]. In addition, in-situ Ar^+ plasma cleaning before metallization has been shown to remove interfacial oxide layers and significantly improve contact uniformity, yielding an order-of-magnitude reduction in contact resistance variability [37].

3.4. Grid stack integration

High-κ/metal gate stacks have been demonstrated using atomic layer deposition (ALD) of HfO_2, achieving equivalent oxide thicknesses well below 1 nm and exhibiting leakage current densities on the order of 10−8 A/cm² at low bias conditions (e.g., sub-1V) [39]. For gate work-function tuning, bilayer metals such as WN/TiN have been shown to enable adjustable effective work functions spanning a range suitable for both n- and p-type applications (from ~4.3 eV to ~5.2 eV), depending on surface composition and defects [40]. Moreover, insertion of ultrathin interfacial dipole layers

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(such as La_2O_3) between a high-κ dielectric and the channel has been reported to significantly reduce threshold voltage variability by modifying the interface dipole, in some cases achieving reductions on the order of tens of percent [40].

3.5. Reducing process damage

To minimize process-induced damage and preserve the structural and electrical integrity of CNTs, fabrication flows increasingly incorporate low-damage etch, anneal, and metallization steps. Mild plasma etching recipes (e.g., oxygen/CH-based chemistries operated at reduced RF power) have been shown to etch and pattern CNT films while producing substantially fewer defects than conventional high-power RIE conditions [41]. Rapid, short-duration thermal treatments such as microwave-assisted annealing can rapidly heal radiation- and etch-induced lattice defects without long, high-temperature exposure that would promote unwanted dopant diffusion [36]. For metallization, thermal or electron-beam evaporation is commonly preferred over energetic sputter deposition for forming contacts to CNTs, because sputtering and plasma processing can introduce additional defects and disorder, whereas e-beam evaporation yields continuous films with less ion bombardment of the underlying nanotubes [42]. Finally, thin ALD Al_2O_3 capping layers or alternative oxide encapsulation schemes have been widely demonstrated to passivate CNT surfaces, suppress oxidation/hysteresis, and improve device stability and mobility retention over time [43].

4. Conclusion

As silicon-based electronics edge closer to their physical scaling limits, carbon nanotube field-effect transistors are drawing attention as a viable route beyond conventional device architectures. Benefiting from their capacity for near-ballistic carrier transport and strong electrostatic control at the atomic scale, CNTFETs have advanced considerably in both conceptual design and fabrication techniques. Recent years have seen notable achievements in producing semiconducting nanotubes with controlled chirality, developing alignment and placement strategies that improve integration, and refining contact structures to facilitate more efficient carrier injection. Together, these efforts have brought CNTFET performance closer to theoretical expectations and underscored their promise as candidates to exceed the practical limits of contemporary silicon technologies.

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