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Research Progress of Carbon Nanotubes for Radio Frequency Electronics

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Abstract: With the rapid development of 5G/6G wireless communications and high-frequency electronic systems, traditional silicon-based semiconductors are gradually approaching their physical and engineering scaling limits. Carbon nanotubes (CNTs), which feature extremely high carrier mobility, high saturation velocity, and ultra-low parasitic parameters, have emerged as the leading candidate material for breaking through the performance bottlenecks of high-frequency RF devices. This paper provides a systematic review of research progress on carbon nanotubes for RF electronics, outlines their structural classifications, and conducts an in-depth comparison of the differences in process controllability and mass production potential among the arc discharge method, laser ablation method, and chemical vapor deposition (CVD) method. In terms of device development, RF devices based on carbon nanotube arrays have surpassed the terahertz frequency band in MOSFET architectures and demonstrated advantages over traditional compound semiconductors in terms of low power consumption and integration in millimeter-wave amplifiers, mixers, and sub-terahertz flexible RF transistors. This paper focuses on the profound impact of underlying material heterogeneity, such as chiral distribution and residual metallic properties, on the modeling and consistency of microwave circuit parameters. To address current engineering bottlenecks, such as the difficulty in achieving ultra-high-purity, controlled fabrication and significant batch-to-batch variability in industrial production, future efforts should prioritize the development of wafer-level high-purity array fabrication, promote three-dimensional heterogeneous integration and chip-level hotspot cooling co-design, and introduce AI-driven multiscale inverse design to accelerate the industrialization of carbon-based RF electronic systems.

Keywords: Carbon nanotubes (CNTs); Radio frequency electronics; Terahertz devices; Flexible RF front end; Material discreteness

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1. Introduction

With the rapid development of 5G/6G wireless communication technology, radio frequency electronics has become a core foundation of modern information society. Traditional silicon-based semiconductor technology, especially CMOS, is gradually approaching the physical and engineering economic limits, which

has propelled the semiconductor industry into the post-Moore era [1]. Carbon nanotubes (CNTs) have become a core candidate material for breaking through the performance bottleneck of traditional semiconductor high-frequency radio frequency devices due to their intrinsic advantages such as extremely high carrier mobility, large saturation velocity, and low parasitic parameters [2].

In recent years, carbon nanotubes have made significant research progress in the field of radio frequency electronics. For example, radio frequency devices based on arrayed carbon nanotubes have successfully achieved a breakthrough in the terahertz band in the metal-oxide-semiconductor field-effect transistor architecture, demonstrating great potential in high-speed broadband communication and flexible electronics. However, existing literature reviews tend to focus on descriptive displays of indicators such as the highest frequency or power gain of the device, lacking critical analysis of how the underlying material properties, such as preparation purity and structural distribution, profoundly affect the device's "high-frequency transmission characteristics" and stability [3].

Although the performance of laboratory-level carbon-based RF devices has reached new highs, there are still obvious theoretical and technical gaps in practical engineering applications and large-scale circuit integration. The core pain point is that the consistency of the underlying material is difficult to guarantee. The inherent distribution differences in diameter and chirality of carbon nanotubes, as well as the metallic carbon nanotube residues that are difficult to eliminate during the preparation process such as chemical vapor deposition (CVD), can cause drastic fluctuations in the threshold voltage of radio frequency field-effect transistors and significantly increase the off-state leakage current [4]. These material-level discreteness severely restricts the reliable modeling and stable integration of key parameters in microwave RF circuit analysis, such as the accurate derivation of open-circuit voltage, transconductance, and parasitic capacitance at each node in the Thevenin equivalent circuit.

This article focuses on comparing the performance advantages, applicable conditions, and industrialization limitations of different technical routes. It provides a systematic review of the fabrication processes, structural classifications, and cutting-edge device developments of carbon nanotubes, with a focus on comparing the process characteristics and applicable conditions of different fabrication routes. The main contribution of this paper is to critically explore the profound impact of the consistency of underlying materials on the high-frequency transmission characteristics and parameter modeling of radio frequency devices, systematically review the breakthroughs of carbon-based devices in the terahertz band and flexible electronics, and point out the current manufacturing bottlenecks and future industrialization development paths.

2. Material properties and preparation principles of carbon nanotubes

2.1. Introduction to carbon nanotube structure

Carbon nanotubes are one-dimensional hollow tubular structures formed by rolling up graphene sheets. Their diameters typically range from 0.7 nm to tens of nanometers, and their lengths can reach from a few micrometers to a few centimeters. Their unique one-dimensional structure, anisotropy, and excellent electrical, thermal, and mechanical properties have attracted widespread attention. As shown in **Figure 1(a)**, CNTs are classified into SWCNTs and MWCNTs according to the number of tube wall layers. SWCNTs are formed by rolling up a single layer of graphene, while MWCNTs are composed of multiple coaxial nested tube walls. The structural categories of CNTs are shown in **Figure 1**.

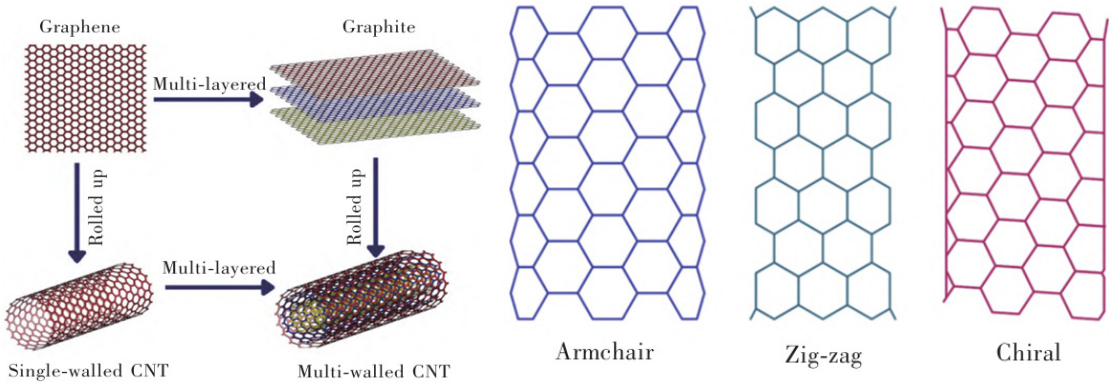


Figure 1. Structural types and classification of carbon nanotubes. (a) Structural diagrams of single-walled and multi-walled CNTs. (b) Three structures of single-walled CNTs.

2.2. Preparation of carbon nanotubes

Current methods for preparing carbon nanotubes include conventional arc discharge (AD), laser ablation (LA), and CVD [5].

The AD method involves evaporating a catalyst-containing graphite anode under inert gas protection using a high-temperature electric arc (3000–4000 ℃), thereby generating CNTs in the cathode deposit [6]. The LA method involves using a laser to bombard a graphite target containing a catalyst in an inert gas, causing its surface to evaporate instantaneously and form a carbon-rich plume. Subsequently, under the influence of a temperature gradient, the plume migrates to a low-temperature region and deposits to form CNTs. The reaction temperature is usually around 3000 ℃. By adjusting the laser wavelength, such as Nd:YAG laser, and pulse frequency, the diameter and chirality of single-walled carbon nanotubes can be controlled, and the purity of the products prepared by this method can reach 70–90%, with extremely high crystallinity [7]. The CVD method involves cracking gaseous, liquid, or solid carbon sources under certain temperature (500–1200 ℃) and catalyst conditions, thereby growing CNTs on the catalyst surface [8].

The study on the preparation of vertically oriented carbon nanotubes based on silicon tips is based on the CVD method to achieve the growth of carbon nanotubes. At high temperatures, the carbon source gas (acetylene) decomposes on the surface of the catalyst (iron nanoparticles) to produce carbon atoms [9]. Due to the small size of the catalyst particles and strong binding force with the substrate, after the carbon atoms are dissolved and saturated, they precipitate from the catalyst surface, forming a bottom growth mode. During growth, the airflow direction guides the overall orientation of carbon nanotubes on the horizontal plane, while the geometry of the silicon tip induces the carbon nanotubes to have an upward climbing tendency. With the support of the silicon tip surface, carbon nanotubes are eventually suspended from the tip, achieving oriented growth perpendicular to the bottom surface of the silicon tip. Traditional localized and oriented preparation methods usually rely on complex and expensive photolithography or template-assisted methods. However, the proposed “ferritin solution contact imprint transfer” method is simple, low-cost, and can accurately position the catalyst on a three-dimensional tip.

2.3. Category comparison and summary

The three mainstream preparation technologies for carbon nanotubes each have their own advantages in terms of process characteristics and application scenarios. The AD method is carried out at extremely

high temperatures (3000–4000 ℃), and the carbon nanotubes prepared have extremely high crystallinity and graphitization degree, but are limited by many impurities and the inability to produce continuously [10]. The LA method is good at preparing single-walled carbon nanotubes with extremely high purity and few defects, which is very suitable for high-performance optoelectronic devices and sensing fields, but the equipment is complex and difficult to mass-produce [11]. In contrast, the CVD method has a lower reaction temperature (500–1200 ℃). Although the crystallinity of the product is slightly inferior to the former two, the process is highly controllable and can precisely adjust the size, chirality, and array morphology of carbon nanotubes. Due to its excellent continuous large-scale production capabilities, CVD has become a core supporting process for building next-generation radio frequency semiconductor devices and large-area electromagnetic protection composite materials. The advantages of the three preparation methods are compared in **Table 1** [12–14].

Table 1. Comparison of the Three Major Fabrication Methods of CNTs

Fabrication method	Common catalysts	Process controllability	Product purity	Product quality	Applicable fields	References
Arc discharge method	Ni, Co, Fe	Low	Often contains impurities such as amorphous carbon, graphite particles, and metal catalyst particles.	Low	Conductive networks, composite materials	[13]
Laser ablation method	Ni, Co	Medium	Concentrated tube diameter distribution; good degree of graphitization	High	Optoelectronic devices, highly sensitive sensors	[13,14]
Chemical vapor deposition (CVD)	Ni, Co, Fe	High	Presence of topological defects and catalyst residues	Medium	RF electronic devices, large-scale integration	[14,15]

3. Major research progress

3.1. Research directions and applications in radio frequency electronics

The core performance indicators of radio frequency devices are the current gain cutoff frequency () and the maximum oscillation frequency (). To boost these two frequencies, the device must have extremely high transconductance, which represents amplification capability, and extremely small parasitic capacitance/resistance. As integrated circuits enter the post-Moore era (below the 3 nm node), traditional silicon-based (CMOS) devices have encountered insurmountable bottlenecks in improving their radio frequency performance due to the sharp increase in leakage current, short-channel effect, and parasitic parameters, and face fundamental challenges [15]. Meanwhile, traditional compound semiconductors such as gallium arsenide (GaAs) have high frequencies but face problems such as low integration and high power consumption, while carbon-based materials are considered one of the important ways to overcome these bottlenecks. Carbon-based radio frequency devices based on arrayed carbon nanotubes have successfully broken this deadlock. For example, in 2025, a carbon-based transistor with a Y-type gate structure was developed [16,17]. By optimizing the gate electrode structure and introducing a Y-type gate, a cutoff frequency of 551 GHz and a maximum oscillation frequency of 1024 GHz were achieved on an arrayed carbon nanotube MOSFET with a gate length of 35 nm. This was the first time that a terahertz frequency was achieved in a MOSFET architecture [18].

The terahertz band (0.3–3 THz) is the core frequency band for next-generation 6G wireless

communication to achieve ultra-high-speed (above 100 Gbps) data transmission. Innovative carbon-based radio frequency devices, such as high-frequency amplifiers and mixers, have demonstrated the ability to stably provide 10–15 dB power gain in the 100–300 GHz band, and their overall performance has initially reached the commercial level. Building on the above work, the research team further fabricated a millimeter-wave (30 GHz) radio frequency amplifier using improved arrayed carbon nanotube radio frequency devices, achieving a gain of 21.4 dB, and its performance is comparable to commercial devices such as GaN and GaAs. This achievement powerfully demonstrates the application potential of carbon-based radio frequency technology in 6G communication, ultra-wideband transceivers, and terahertz imaging systems, providing revolutionary underlying hardware support for future 6G base stations, ultra-wideband transceivers, and phased array systems [19].

A team led by Hu Youfan and Peng Lianmao at Peking University, in collaboration with Eric Pop's team at Stanford University, reported in *Nature Electronics* in 2026 a flexible radio frequency transistor based on an array of oriented carbon nanotubes, achieving stable operation in the frequency band above 100 GHz for the first time. This study solved the problem of the self-heating effect caused by the poor thermal conductivity of flexible substrates through electro-thermal co-design. The device achieves a peak current gain cutoff frequency () of 152 GHz and a power gain cutoff frequency () of 102 GHz on a 2 μm thick polyimide (PI) substrate, with DC power consumption below 200 mW/mm. This achievement marks the first breakthrough of flexible radio frequency transistors in the Asia-Pacific Hertz band, laying a key technological foundation for the development of 6G flexible terminal equipment [20].

Compared to traditional compound semiconductors, carbon-based radio frequency devices not only have extremely high frequencies, but can also operate at lower operating voltages and quiescent power consumption. Furthermore, the inherent macroscopic flexibility of carbon nanotube films enables the integration of these high-performance terahertz devices onto ultrathin flexible substrates, paving the way for future wearable radio frequency front-ends, epidermal medical monitoring signal amplifiers, and flexible conformal radar. Its structural performance is shown in **Figure 2** [21].

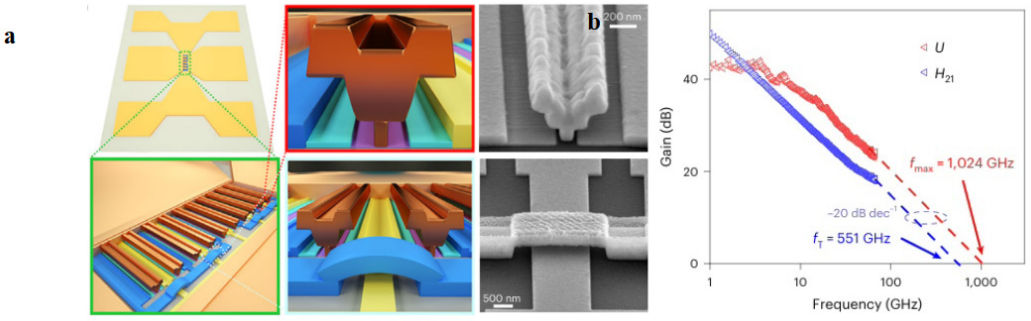


Figure 2. Structure and performance characteristics of A-CNT MOSFETs
(a)Schematic and SEM Images of a 10-finger CNT RF Transistor with Y-gate and Air-bridge
(b)Current Gain and Power Gain Versus Frequency of the 35 nm-Lg Champion RF transistor. The slope of the extension lines is −20dB/dec.

3.2. Comparison of representative studies and summary

In 2025, amplifiers using Y-gates will achieve a maximum power gain of 21.4 dB in the 30 GHz band, with overall performance initially reaching the level of commercial millimeter-wave RF amplifiers. In 2025,

a team from Peking University developed a Y-shaped gate and air bridge structure suitable for carbon nanotubes, reducing the gate length to 35 nm. Its maximum oscillation frequency exceeds 1024 GHz, achieving a breakthrough in terahertz frequency for the first time, and its extrinsic cutoff frequency exceeds 551 GHz. In 2025, a team from Peking University fabricated a monolithic microwave integrated circuit based on arrayed carbon nanotube devices, breaking through the integration bottleneck of Ka-band reflective phase shifters. The chip achieves 4 dB insertion loss and 55° phase shift in the 40 GHz band, and a maximum phase shift of 65° in the 42 GHz band [21]. The amplifier performance is shown in **Figure 3** [21].

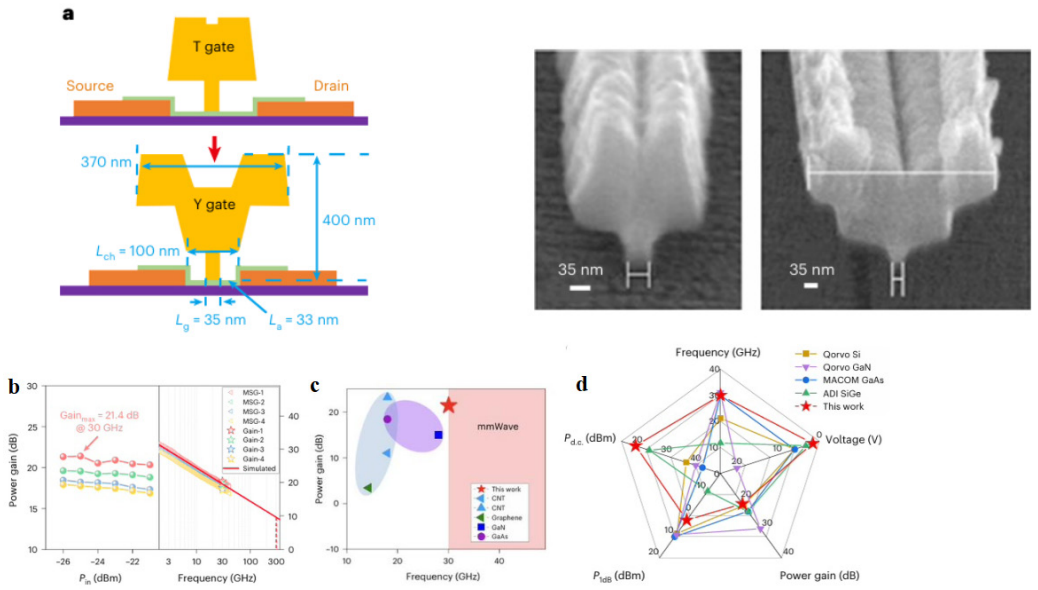


Figure 3. Structure and Performance Characteristics of A-CNT MOSFETs

(a)Schematic and SEM Images of CNT RF Transistor with Y-gate and Air-bridge

(b)Left: Power Gain versus Input Power Data for Amplification Tests of Four Devices at a Frequency of 30 GHz. Right: Power Gain of Four Amplifier and Corresponding Pad De-embedding Power Gain Curves. The measurement frequency is 30 GHz.

(c)Power Gain Compared with Other Amplifiers Based on Different Materials. The red stars represent the best CNT RF transistors shown in (a).

(d)Comprehensive RF Performance Including Frequency, Working Voltage, Gain, 1 dB Compression Point (P1dB), and PDC Compared to that of RF Amplifiers42 Made by the Others

In 2021, a team from Peking University successfully developed a radio frequency field-effect transistor with a gate length reduced to 50nm based on highly oriented arrayed carbon nanotube materials, and further constructed a K-band small-signal amplifier for microwave high-frequency communication. Thanks to the near-ballistic transport advantage brought about by the ultra-high carrier mobility of the arrayed carbon nanotubes, the device exhibits excellent gate electrostatic control capability and extremely high intrinsic transconductance. At an operating frequency of 18 GHz, the amplifier achieved a maximum power gain of up to 23.2 dB, which not only significantly reduced parasitic parameter losses at high frequencies, but also fully demonstrated the practical potential of carbon-based RF devices in millimeter-wave low-noise amplification and high-gain preamplifier circuits [22].

In the direction of nonlinear microwave radio frequency functional circuits, the Peking University team further reduced the gate length of carbon-based transistors to 50 nm in 2023 and successfully developed a high-performance active mixer. The device takes full advantage of the excellent gate electrostatic control capabilities and low parasitic parameters of carbon nanotubes, and exhibits stable mixing characteristics in an ultra-wide frequency band of 18 to 40 GHz, with a conversion gain between -12.7 and -17 dB. More importantly, thanks to the near-ballistic transport advantage brought by the one-dimensional conductive channel of carbon nanotubes, the input third-order intercept point (IIP3) of the mixer has exceeded 25 dBm, showing extremely high dynamic range and anti-signal distortion capabilities. Its comprehensive amplification and frequency conversion performance has reached the leading level among similar nanomaterial RF devices [23].

In 2025, a team from Hunan University and Peking University developed a high-performance carbon-based amplifier on an ultra-thin plastic substrate. The device achieves a DC voltage gain of more than 34 under a 4 V supply voltage, and a gain of 41 dB when the gain-bandwidth product is 200 kHz, providing a lightweight, low-power signal amplification solution for wearable health monitoring equipment [24].

4. Practical application and higher-level development

4.1. Practical applications of carbon nanotubes

With their extraordinary electrical, mechanical, and thermal intrinsic properties, CNTs have shown great application potential and strategic value in many cutting-edge cross-cutting fields.

In the field of radio frequency electronics, carbon nanotubes exhibit extremely high carrier mobility and saturation velocity due to the near-ballistic transmission advantages brought by their one-dimensional quantum wire characteristics. At the same time, their ultra-thin body structure demonstrates excellent gate electrostatic control capabilities under physical shrinkage conditions, which can effectively suppress short-channel effects and significantly reduce parasitic capacitance. Based on these breakthrough material properties, scientists have successfully developed core high-frequency devices such as Y-type/T-type gate transistors, K-band high-gain amplifiers, and low-loss mixers. Their cutoff frequency (f_T) and maximum oscillation frequency (f_{max}) have both successfully exceeded the 100 GHz mark, bringing a revolutionary leap to RF front-end technology [25].

Future 6G networks and low-orbit satellite communication systems are highly dependent on millimeter wave (mmWave) and even terahertz (THz) frequency bands to achieve ultra-high data throughput at the Tbp/s level. Traditional RF chips often face severe gain attenuation and linearity deterioration in these extremely high-frequency bands. Arrayed carbon nanotube devices not only provide high-frequency characteristics that meet the terahertz frequency band response, but also maintain excellent signal linearity, an extremely high third-order intercept point OIP3, and low power consumption, effectively filling the technical gap of existing semiconductors in ultra-wideband and high-frequency band communications.

Modern phased array radar systems require the integration of thousands of tiny radio frequency transceiver (T/R) components. Carbon nanotube devices have two core advantages: first, the potential for heterogeneous integration, which does not require the demanding lattice matching of traditional compound semiconductors and can be directly three-dimensionally integrated on standard silicon-based CMOS circuits; second, excellent heat dissipation and stability. This allows future radar RF front-ends to be smaller in size

and have denser arrays, thereby greatly improving the accuracy of beamforming, target resolution, and the overall anti-interference ability of the system. It has huge potential in autonomous driving millimeter-wave radars and military phased array systems.

Unlike silicon, gallium arsenide or gallium nitride, which are hard and brittle, super-aligned carbon nanotube films are naturally extremely mechanically flexible and resistant to bending [26]. Seamlessly integrating high-frequency CNTs into radio frequency circuits on flexible polymer substrates can create high-performance "conformal antennas" and flexible radio frequency transceiver modules. This provides an irreplaceable hardware solution for smart medical wearable devices, attachable Internet of Things (IoT) sensors, and conformal radars that need to fit on complex curved surfaces.

4.2. Higher-level development of carbon nanotubes

Future development is no longer limited to macro-scale aerogels or composite sheets, but will evolve towards micro-nano multi-functional integration at the chip level and packaging level. Using technologies such as CVD to directionally grow ultra-high-purity carbon nanotube arrays inside RF front-end chips or on packaging substrates, micrometer or even nanoscale micro electromagnetic isolation trenches (EMI Trenches) can be constructed. This structure physically blocks electromagnetic crosstalk between high-frequency signal channels, enabling ultra-low-loss transmission and high-isolation shielding of millimeter-wave and terahertz signals. More importantly, with the excellent intrinsic one-dimensional structure and extremely high axial thermal conductivity of carbon nanotubes, the array can be used as an efficient local micro-nano thermal bridge to in-situ export the ultra-high heat flux density generated by active devices such as power amplifiers at the microscale, thereby achieving in-depth collaborative design of high-frequency electromagnetic isolation and heat dissipation of local hotspots of high-power chips in the same physical space [27].

In advanced RF front-end architectures such as phased array radar and millimeter-wave ultra-wideband base stations, the signal linearity of RF devices, such as third-order intercept point OIP3 and 1 dB compression point, directly determines the system's anti-interference capability and communication quality under high-density electromagnetic spectrum and complex modulation formats. Early carbon tube radio frequency devices can easily form short-circuit parasitic paths due to residual metallic carbon tubes (m-CNTs) in random networks, resulting in a sharp increase in device leakage current, aggravation of nonlinear distortion, and serious deterioration of high-frequency radio frequency gain and signal saturation.

As wireless communications evolve towards high-order modulation and high-density arrays, the RF receiving front-end places stringent requirements on the large dynamic range and high linearity of the device. Traditional carbon tube devices are prone to significant intermodulation distortion under strong signal excitation due to uncontrollable chirality and residual metallic carbon tubes. Currently, relying on highly selective non-covalent encapsulation purification technology of conjugated polymers such as polyfluorene, the purity of semiconductor carbon tubes has crossed the 99.9% threshold [28]. Coupled with the nanoscale self-aligned T-shaped gate structure, the arrayed carbon tube RF transistor achieves a high transconductance response of 310 μS/μm while significantly reducing the gate series resistance. The synergy of high-purity semiconductor channels and optimized electrode structures gives carbon-based RF devices excellent input/output linearity, which not only effectively expands the dynamic operating window of amplifiers under high-power input, but also provides a high-performance hardware foundation for the development of future high-interference-resistant phased array T/R components and ultra-wideband low-noise amplifiers (LNA) [29].

5. Current challenges and existing issues

5.1. Material controllable preparation and purity bottlenecks

Carbon nanotubes naturally exhibit a mixed state of metallic and semiconducting properties during the growth process. High-frequency RF electronic devices require the use of semiconductor single-walled carbon nanotubes with extremely high purity (usually > 99.9999%) to completely eliminate leakage current and device short circuits caused by metallic carbon tubes. However, so far only in the laboratory has the purity of semiconductor carbon nanotubes exceeding 99.9999% been successfully achieved, which is the highest semiconductor purity reported by aqueous phase separation technology to date [30]. Current industrial-grade CVD and other preparation or post-processing purification technologies still have certain problems in balancing extremely high purity, high yield, and low cost. Large-scale industrial preparation often inevitably introduces topological defects in the tube wall, amorphous carbon, and metal catalyst residues. These impurities can cause serious electron scattering at the microscopic level, which not only degrades the high-frequency transmission characteristics of radio frequency signals, but also interferes with the intrinsic polarization and impedance matching design of macroscopic electromagnetic absorbing materials [31].

5.2. Engineering difficulties of composite materials and macroscopic applications

When preparing multi-dimensional broadband electromagnetic absorption aerogels or stealth coatings, carbon nanotubes are prone to severe agglomeration in solvents or polymer matrices due to their large specific surface area and strong van der Waals forces [32]. In industrial-level mass mixing and processing, achieving nanoscale uniform dispersion at high concentrations while avoiding mechanical shear forces that cut the carbon tubes and damage their conductive networks is the core pain point in preparing high-performance absorbing materials [33].

Carbon nanotubes produced in different batches and process paths have significant fluctuations in key parameters such as tube diameter, aspect ratio, purity, and dielectric/magnetic permeability [34]. The discrete nature of this material index directly leads to the instability of the final radio frequency chip performance or the electromagnetic stealth skin between batches, which seriously restricts its large-scale installation in high-reliability fields such as aerospace, military radar, and 6G communications [35].

6. Conclusions and outlook

In view of the current situation, where existing reviews show the macroscopic performance of multi-directional devices but lack critical analysis of the underlying physical mechanisms, this article systematically explores the deep impact of the intrinsic characteristics of CNT materials on the high-frequency transmission stability of radio frequency electronic devices. Research results show that devices based on arrayed carbon nanotubes, with extremely high carrier mobility and excellent minimal parasitic parameters, not only effectively overcome the short-channel effect and size scaling bottleneck of traditional silicon-based CMOS devices in the post-Moore era, but also successfully achieve a breakthrough in the terahertz frequency band in the metal oxide semiconductor field-effect transistor MOSFET architecture. It clarifies the core supporting position of the CVD method in building the next generation of radio frequency semiconductor devices, and provides a reliable theoretical basis for the industrialization evaluation of carbon-based radio frequency front-ends in 6G communications and high-frequency flexible electronics.

Despite the revolutionary potential of carbon nanotubes in radiofrequency electronics, there are certain

limitations to this review and current research in this field. First of all, this article mainly focuses on the discussion of high-frequency transmission characteristics at the device level and basic microwave circuit level. There is still insufficient discussion on the long-term stability, aging failure mechanisms, and high-frequency crosstalk issues of carbon-based radio frequency chips in complex large systems. Secondly, the current data on the ultra-high purity purification of single-walled semiconductor carbon tubes (> 99.9999%) in the current literature are mostly derived from the ideal laboratory environment, and have not yet been able to fully prove the true impact of impurity residues on the macroscopic parasitic parameters of actual microwave RF circuits in industrial-level large-area wafer manufacturing. The differences in metallic carbon tube residues and diameter distribution that are difficult to completely eliminate severely restrict the stable integration of key node parameters.

Disclosure statement

The author declares no conflict of interest.

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