

Article

Small-Signal Modeling and Nonlinear Characterization of Aligned Carbon Nanotube Schottky Barrier Diodes

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Abstract

Schottky barrier diodes (SBDs) based on low-dimensional materials are of interest for high-speed electronics due to their intrinsic nonlinear transport characteristics. In this work, aligned carbon nanotube Schottky barrier diodes (ACNT-SBDs) were systematically studied through electrical characterization, small-signal modeling, and large-signal nonlinear measurements. Devices with channel widths ranging from 50 to 500 μm were fabricated to examine size-dependent direct-current and high-frequency behavior. Clear Schottky rectification and pronounced geometry-dependent characteristics were observed, with the widest device achieving an intrinsic cutoff frequency of up to 282 GHz. Based on measured S-parameters, a refined small-signal model incorporating a parallel resistance–constant phase element (CPE) branch was developed, providing substantially improved agreement with measured S- and Y-parameters and phase response compared with the classical model. The extracted CPE parameters exhibit systematic dependence on channel width, indicating distributed junction charge dynamics associated with carbon nanotube interfaces. Furthermore, the large-signal nonlinear behavior was evaluated using an anti-parallel diode configuration, achieving a third-harmonic output power of -22.58 dBm at 30 GHz under zero-bias operation. This work provides a comprehensive experimental and modeling framework for understanding the high-frequency and nonlinear behavior of ACNT-SBDs.

Keywords: aligned carbon nanotubes; Schottky barrier diode; small-signal model; nonlinear characterization; frequency response

1. Introduction

Schottky barrier diodes (SBDs) are fundamental building blocks in high-speed electronics due to their intrinsic nonlinear current–voltage (I–V) characteristics. With the continuous increase in operating frequencies and the scaling of device dimensions, low-dimensional materials have attracted significant attention as promising candidates for next-generation Schottky devices. Among them, carbon nanotubes (CNTs) offer unique advantages, including high carrier mobility, quasi-one-dimensional transport, and compatibility with planar fabrication processes, making CNT-based Schottky diodes particularly attractive for high-frequency operation [1–4].

Over the past decade, extensive efforts have been devoted to the development of CNT-SBDs, with demonstrated capabilities in rectification, detection, and frequency multiplication at radio-frequency (RF) and millimeter-wave (mmWave) frequencies [5–11]. Most reported studies, however, primarily focus on direct-current (DC) characteristics or limited



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high-frequency metrics, while systematic investigations that combine device geometry scaling, frequency-domain characterization, and nonlinear response remain relatively limited. In addition, small-signal equivalent circuit models for CNT-SBDs are commonly based on simplified RC representations [12,13], which may not fully capture frequency-dependent effects arising from interfacial nonuniformity, distributed transport pathways, and complex charge relaxation processes inherent to CNT-based junctions. Understanding the high-frequency behavior of CNT-SBDs therefore requires not only evaluating conventional performance figures such as cutoff frequency (f_c), but also examining the underlying small-signal response and its limitations. In this context, frequency-dependent deviations in admittance magnitude and phase may indicate the presence of distributed junction charge dynamics that cannot be adequately described by a single characteristic time constant.

In this work, we present an investigation of aligned carbon nanotube Schottky barrier diodes (ACNT-SBDs). Devices with a fixed electrode spacing and channel widths ranging from 50 to 500 μm are fabricated and characterized to examine size-dependent DC and high-frequency electrical behavior. Based on measured S-parameters, a refined small-signal equivalent circuit model is developed to describe the frequency-domain response of ACNT-SBDs beyond the classical resistor-capacitor (RC) framework. In addition, the large-signal nonlinear characteristics of the devices are experimentally evaluated through third-harmonic generation using an anti-parallel diode configuration, without impedance matching or circuit-level optimization. This comprehensive study provides an integrated experimental and modeling perspective on the high-frequency and nonlinear behavior of ACNT-SBDs.

2. Materials and Methods

Figure 1a presents a three-dimensional schematic of the fabricated ACNT-SBD integrated with standard two-port ground-signal-ground (GSG) probe pads. The GSG configuration was incorporated to enable both DC and high-frequency electrical characterization. These probe pads were defined by conventional photolithography followed by electron-beam evaporation (EBE) of titanium/gold (Ti/Au) with a thickness of 500 nm, ensuring compatibility with microwave probing systems. The pad geometry was optimized to reduce parasitic effects and minimize signal reflection during high-frequency measurements. In addition, dedicated open and short structures were fabricated and measured on the same wafer to perform de-embedding of pad-related parasitic capacitances and resistances. The open structure was used to extract pad capacitance, while the short structure enabled removal of series parasitic inductance and resistance. The measured S-parameters were subsequently de-embedded prior to small-signal parameter extraction. A scanning electron microscopy (SEM) image of the fabricated diode structure is shown in Figure 1b, highlighting the metal-nanotube junction region of the ACNT-SBD. The device fabrication process began with the preparation of ACNT array films on quartz substrates using a dimension-limited self-alignment (DLSA) method. The resulting ACNT arrays exhibit high alignment uniformity with a linear density of approximately $230 \text{ CNT} \cdot \mu\text{m}^{-1}$. A representative SEM image of the as-prepared ACNT array is provided in Figure 1c. Prior to device patterning, the ACNT films were subjected to surface conditioning and thermal treatment to improve nanotube cleanliness and interfacial contact quality. Specifically, the samples were annealed at 600 $^{\circ}\text{C}$ for 3 h in a mixed N_2/H_2 atmosphere. This high-temperature annealing step effectively removes residual polymer species originating from the nanotube assembly process and reduces interfacial contamination, thereby facilitating improved electrical coupling between the carbon nanotubes and subsequently deposited metal electrodes.

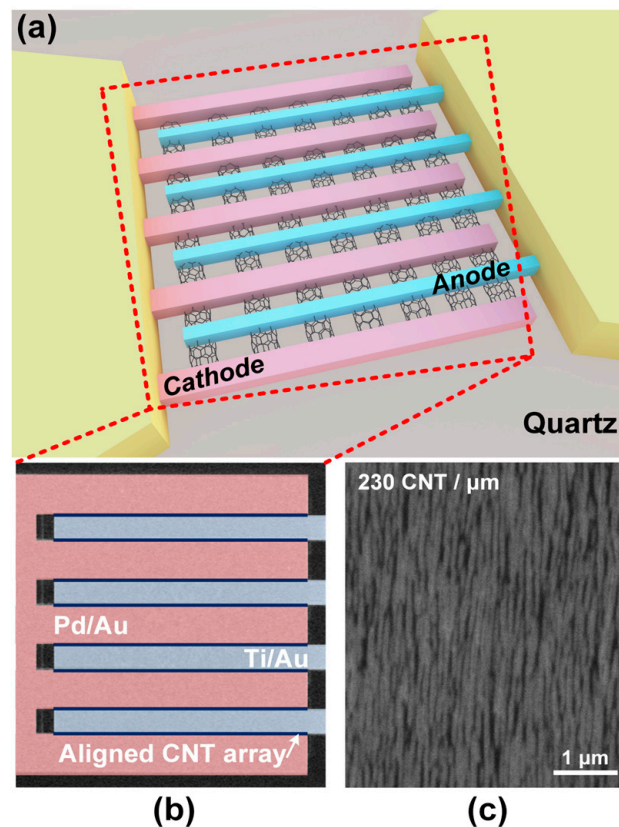


Figure 1. (a) Structure of the ACNT-SBD; (b) SEM image of the diode; (c) SEM image of ACNTs array with density of $230 \text{ CNT} \cdot \mu\text{m}^{-1}$.

The active device region was then defined using electron-beam lithography (EBL), followed by oxygen plasma etching to selectively remove carbon nanotubes outside the designed channel area. This patterning process allows precise control of the effective channel geometry while suppressing parasitic conduction paths. Metal contacts were subsequently formed by EBE. A Ti/Au (20/80 nm) metal stack was employed as the Schottky anode, while a palladium/gold (Pd/Au, 20/80 nm) stack was used as the ohmic cathode. The selection of contact metals was guided by their work-function alignment and established compatibility with CNTs, enabling the asymmetric contact characteristics required for ACNT-SBD operation.

The sample covered with the ACNT array film was annealed in a tube furnace (Thermo Scientific Lindberg/Blue M Moldatherm 1100 °C, Thermo Fisher Scientific, Waltham, MA, USA). SEM images of the ACNT array film and ACNT-SBD were obtained using a Sigma 300 microscope (ZEISS, Oberkochen, Germany). Electrical characteristics of the ACNT-SBDs were measured at room temperature using a Keithley 4200 semiconductor characterization system (Keithley Instruments, Cleveland, OH, USA) combined with a probe station (MPI TS200-SE, MPI Corporation, Munich, Germany). Patterning of the ACNT-SBDs was carried out using an EBL system (Raith 150, Raith GmbH, Dortmund, Germany), and metal deposition was performed using an EBE system (Kurt J. Lesker Company, Jefferson Hills, PA, USA).

3. Results and Discussion

3.1. Electrical and RF Characterization of ACNT-SBDs

Figure 2 shows the current–voltage (I–V) characteristics of the fabricated ACNT-SBDs. The electrode spacing was fixed at 120 nm, while the channel width was varied ($W = 50, 60, 100, 200, 300, \text{ and } 500 \mu\text{m}$) to investigate the impact of device scaling on electrical

performance. All devices show clear rectifying behavior with strongly nonlinear I–V characteristics, confirming Schottky diode operation. At the same bias voltage, diodes with larger channel widths deliver higher output currents. This trend can be attributed to the increased metal–CNT contact area, which introduces a greater number of parallel carrier transport pathways and consequently enhances the overall conduction capability of the active region. The ACNT-SBD with a channel width of 100 μm achieves a forward current density of $0.12 \text{ mA} \cdot \mu\text{m}^{-1}$ at a bias voltage of -1.2 V . The inset presents the I–V characteristics plotted on a semi-logarithmic scale. Under reverse bias, all devices exhibit low leakage currents with only minor variations across different channel widths, indicating effective junction control and good interface uniformity as the device dimensions are scaled.

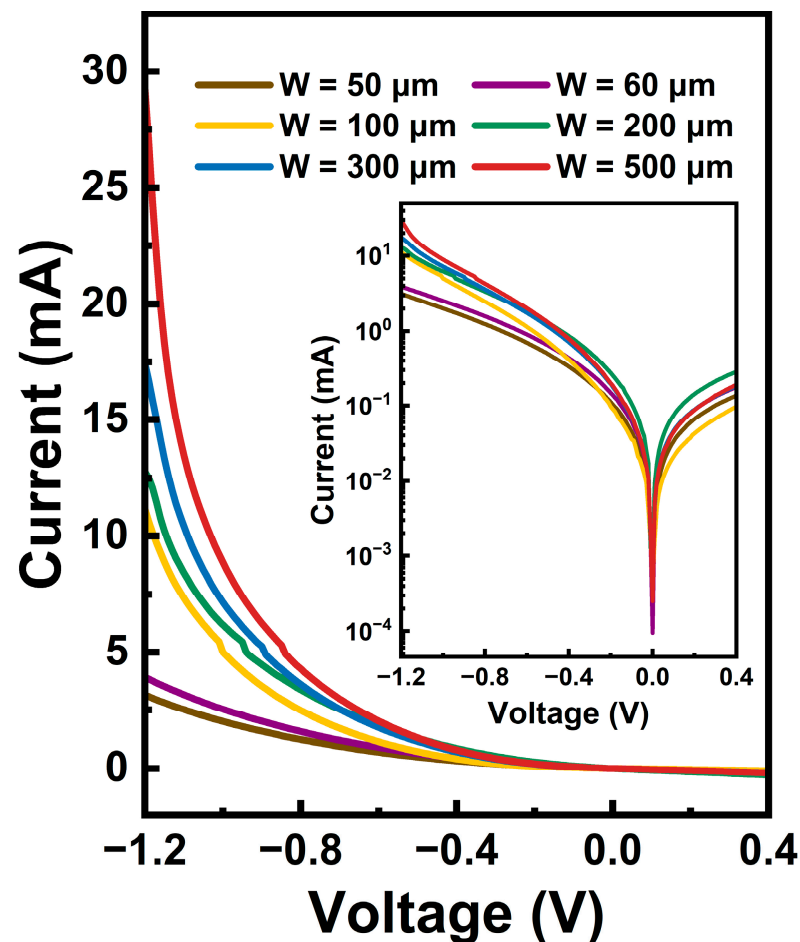


Figure 2. Measured I–V characteristics of p-type ACNT-SBDs with different channel widths. Insets: semi-log plot of the I–V curves.

Larger channel widths can significantly enhance the DC conduction current of the devices; however, the overall performance is not determined by the static current alone and is simultaneously constrained by series contact resistance (R_s) and junction capacitance (C_j). Figure 3 presents the extracted R_s and C_j for diodes with different channel widths. As the channel width increases, R_s exhibits an overall decreasing trend, reflecting the increased number of parallel transport pathways and the reduced effective conduction resistance. For ACNT-SBD devices, the junction capacitance does not originate from a bulk depletion region as in conventional three-dimensional semiconductors, but is instead dominated by charge modulation processes occurring at the metal–CNT contact region. With increasing channel width, a larger number of CNTs participate in the junction charge response, leading to an expansion of the effective metal–CNT junction area and a corresponding increase in

the overall C_j . These results indicate that while device scaling is beneficial for reducing the series resistance, it inevitably introduces a larger parasitic capacitive load.

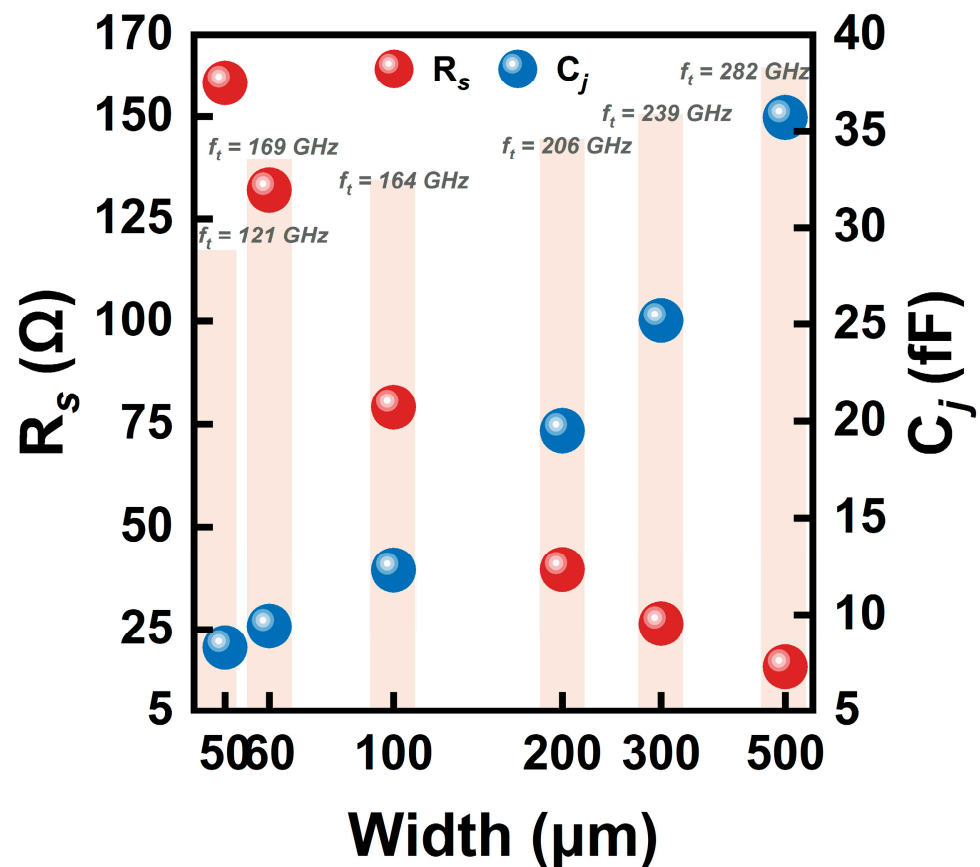


Figure 3. Extracted on-state contact resistances, off-state junction capacitance and cutoff frequencies of ACNT-SBDs.

Under a first-order approximation dominated by RC delay, the cutoff frequency (f_c) of ACNT-SBD can be evaluated based on the extracted R_s and C_j , defined as

$$f_c = \frac{1}{2\pi R_s C_j} \quad (1)$$

Figure 3 also summarizes the extracted cutoff frequencies for diodes with different channel widths, among which the device with a channel width of 500 μm achieves the highest f_c of 282 GHz.

Table 1 further compares the f_c achieved in this work with those of diodes based on CNTs, 2D materials, metal oxides, and organic semiconductors [14–21]. Benefiting from the exceptionally high carrier mobility of ACNT, the present device demonstrates superior high-frequency characteristics, highlighting its favorable high-frequency performance relative to previously reported devices. For ACNT-SBD devices, optimization of high-frequency performance cannot be simply reduced to minimizing a single parasitic parameter, but instead depends on the overall balance established by device geometry between conduction capability and junction charge response. This finding provides more targeted guidance for structural design of ACNT-SBDs in RF applications, and further indicates that, for one-dimensional nanomaterial array devices, conventional design intuition based solely on minimizing junction capacitance must be evaluated in the context of the specific device architecture.

Table 1. Cutoff frequencies of ACNT-SBDs. Comparison with CNT, 2D materials, metal oxides, and organic semiconductors devices.

Material	MoS ₂	ZnO	WSe ₂	Graphene	a-IGZO	CNT	This Work ¹
Cutoff frequency (GHz)	10	100	27	2.4 30	1 2.45	0.2 8	121–282

¹ The cutoff frequency range corresponds to ACNT-SBDs with channel widths of 50, 60, 100, 200, 300, and 500 μm measured under zero-bias conditions. The corresponding experimental data are presented in Figure 3.

These results highlight that the high-frequency performance of ACNT-SBDs is governed by a geometry-dependent balance between conduction capability and junction charge response, which motivates a more detailed investigation of the underlying frequency-dependent charge dynamics, as discussed in Section 3.2.

3.2. Modeling of ACNT-SBDs

Small-signal modeling of the fabricated ACNT-SBDs based on measured S-parameters is essential for both advancing their high-frequency applications and deepening the understanding of their underlying physical mechanisms. Small-signal models for CNT-SBD are generally divided into an intrinsic core module and a parasitic module [13]. The intrinsic core module describes carrier transport across the metal–CNT Schottky junction as well as the associated junction capacitance response, while the parasitic module mainly accounts for high-frequency nonidealities introduced by the GSG pads, interconnects, and measurement environment. In classical models, the intrinsic core typically consists of the junction resistance R_j , junction capacitance C_j , and series resistance R_s . Here, R_j represents the nonlinear conductance of the Schottky junction, C_j characterizes the dominant capacitive response of the junction region, and R_s corresponds to the ohmic contact resistance between the metal and carbon nanotubes as well as the channel resistance. Previous small-signal models for CNT-SBDs generally adopt this lumped RC framework [12,13], where the junction is represented by a bias-dependent resistance–capacitance pair combined with parasitic resistances and pad capacitances. These models have proven effective in describing the primary high-frequency response and estimating the cutoff frequency. Nevertheless, the lumped RC representation inherently assumes that the junction capacitance can be characterized by a single effective parameter with a unique relaxation time. Moreover, the classical framework does not explicitly distinguish between different physical origins of capacitive behavior, such as contact-induced capacitance, interface-related effects, or structural nonuniformity within the CNT array. However, during the modeling of the diodes investigated in this work, it was found that these parameters alone are insufficient to fully capture the small-signal behavior of the ACNT-SBDs. In practical S-parameter fitting, the classical model exhibits systematic deviations at low frequencies and in phase response that cannot be eliminated through parameter adjustment, indicating the presence of additional charge response processes not accounted for by the conventional RC network.

Based on these observations, the equivalent circuit topology of the ACNT-SBD was refined beyond the classical small-signal model, as shown in Figure 4. First, to describe nonideal contact behavior potentially introduced by residual polymers from the CNT sorting and assembly process, an additional ohmic capacitance C_s was introduced into the intrinsic block [12]. This capacitance is primarily related to the effective electrode contact area, decreases with reduced device size, and shows negligible dependence on the applied bias. Furthermore, ACNT-SBDs inherently exhibit material and structural nonuniformities, including nanotube-to-nanotube variations in diameter and chirality, spatial fluctuations in metal–CNT contact quality, and interfacial trap states formed during fabrication and

transfer processes. These factors give rise to multiple charge capture–release processes with distinct characteristic time constants distributed throughout the device. As a result, the junction response cannot be represented by a single lumped capacitance; instead, it reflects a spatially distributed relaxation behavior that manifests as frequency-dependent dispersion in both magnitude and phase. To address this limitation, a coupling resistance R_d and a constant phase element (CPE) were introduced in parallel with the junction branch to capture distributed charge dynamics in the device.

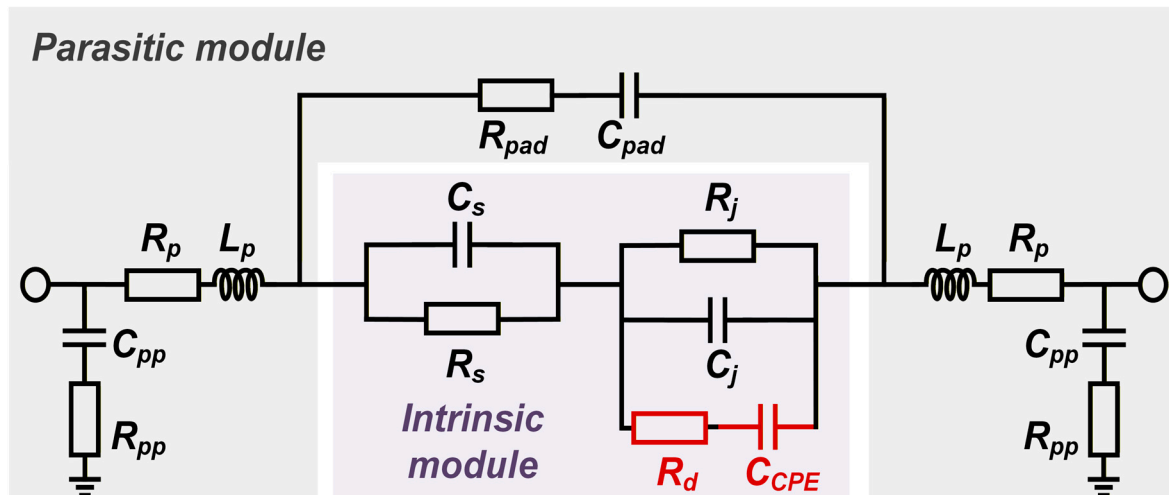


Figure 4. Small-signal model of the ACNT-SBD.

The CPE is an equivalent element widely used to describe nonideal capacitive behavior, distributed relaxation, and dispersive admittance. Its physical meaning does not correspond to a single geometrically defined capacitance; rather, it provides a compact representation of a continuous distribution of time constants using a small number of parameters. The admittance of a CPE can be expressed as

$$Y_{CPE}(\omega) = Q(j\omega)^n, \quad 0 < n < 1, \quad (2)$$

where ω represents the angular frequency, Q is the magnitude factor representing the strength of the dispersive process, and n is the power-law exponent that determines the phase deviation from the ideal capacitive value of 90° . When $n < 1$, the CPE includes both energy storage and dissipation components, enabling effective description of non-Debye charge response behavior. This modeling approach has been widely applied in the analysis of semiconductor interface states, electrochemical systems, and low-dimensional material devices [22]. In ACNT-SBD devices, the junction response is often governed by multiple spatially distributed charge processes rather than a single characteristic time constant. These processes include trap-assisted charging, contact-induced barrier fluctuations, and nanotube ensemble inhomogeneity. As a consequence, the frequency-domain behavior exhibits power-law characteristics that are well described by a CPE. In this framework, the CPE provides a compact representation of the distributed relaxation spectrum originating from structural and interfacial nonuniformities in the ACNT array.

Figure 5 compares the measured S-parameters with fitting results obtained using the classical model and the proposed CPE-based model. The S-parameters were measured and fitted over the frequency range of 100 MHz to 67 GHz. While both models provide reasonable agreement in the high-frequency regime, the classical model fails to simultaneously reproduce the magnitude and phase behavior at low frequencies. In contrast, the CPE-based model achieves consistently improved fitting accuracy over the entire frequency range.

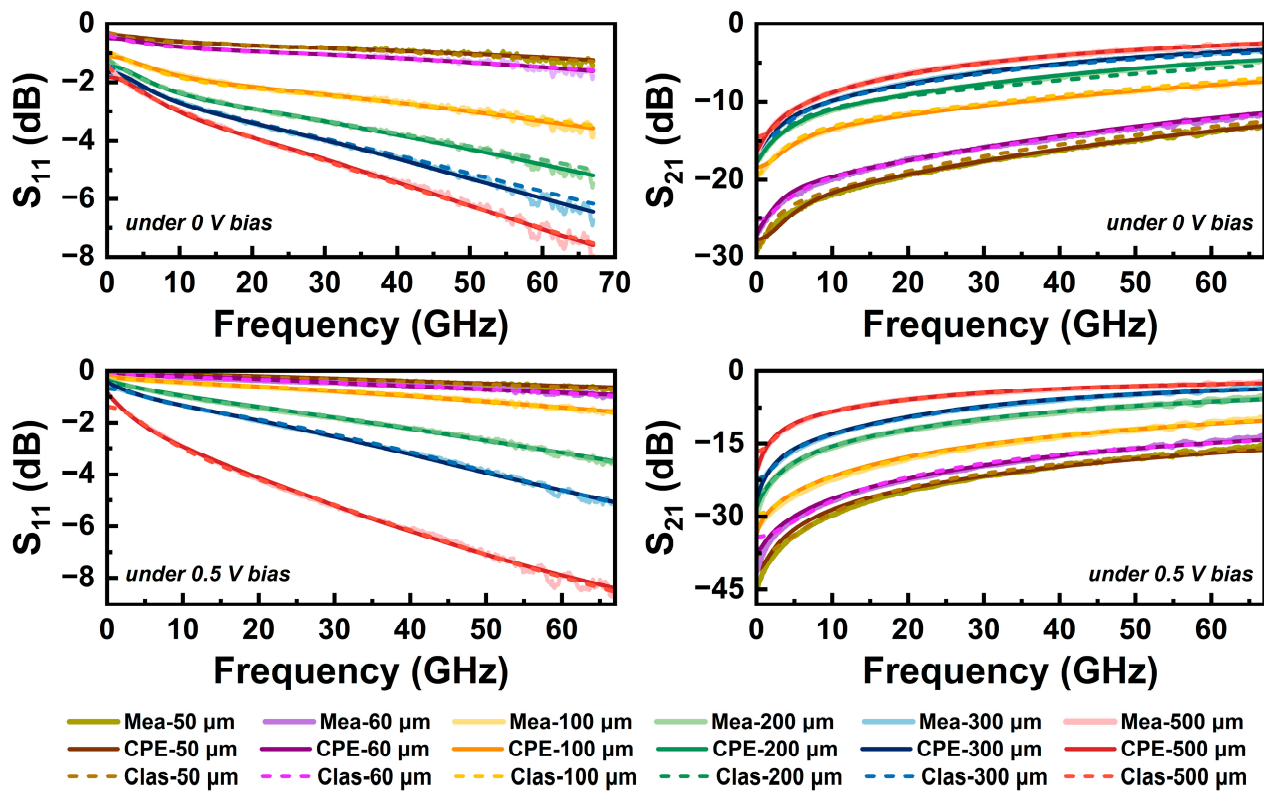


Figure 5. Comparison of S-parameters obtained from measurement (Mea), CPE-based model (CPE), and classical model (Clas) for ACNT-SBDs with different channel widths under various bias voltages.

To further elucidate the physical origin of this difference, Figure 6 presents the measured real part, imaginary part, and phase response of the Y_{11} parameter for devices with different channel widths ($W = 50\text{--}500\text{ }\mu\text{m}$) under zero-bias conditions, while the corresponding fitted results under a 0.4 V bias are shown in Figure S1. Since the Y-parameters directly represent the parallel admittance at the device port, any charge process with a distinct response speed contributes additively to the measured admittance. The experimental results reveal a clear power-law behavior in $\text{Re}\{Y_{11}\}$, while $\text{Im}\{Y_{11}\}$ and the phase response exhibit systematic deviations from the behavior expected for an ideal junction capacitance. These features reflect a frequency-dependent balance between energy storage and dissipation. The classical model, which only includes C_j , is unable to reproduce such frequency-dependent phase deviations. By contrast, after introducing the parallel R_d –CPE branch, the model can accurately capture both magnitude and phase responses across different device sizes. This improvement arises because the CPE effectively describes power-law dispersive behavior associated with interfacial nonuniformity and multiple charge relaxation processes. Consequently, the proposed model maintains consistent fitting accuracy across a wide range of device dimensions, whereas the classical model does not.

Table 2 summarizes the extracted CPE parameters Q and n for devices with different channel widths. Both parameters exhibit an overall increasing trend with increasing device size. The increase in Q reflects the larger effective junction area and stronger overall admittance contribution from the nanotube ensemble.

Table 2. Extracted CPE parameters (Q and n) for ACNT-SBDs with different channel widths.

Parameters	$W = 50\text{ }\mu\text{m}$	$W = 60\text{ }\mu\text{m}$	$W = 100\text{ }\mu\text{m}$	$W = 200\text{ }\mu\text{m}$	$W = 300\text{ }\mu\text{m}$	$W = 500\text{ }\mu\text{m}$
Q	8.4×10^{-12}	8.6×10^{-12}	9.3×10^{-12}	1.1×10^{-11}	1.3×10^{-11}	2.9×10^{-11}
n	0.59	0.66	0.70	0.74	0.77	0.78

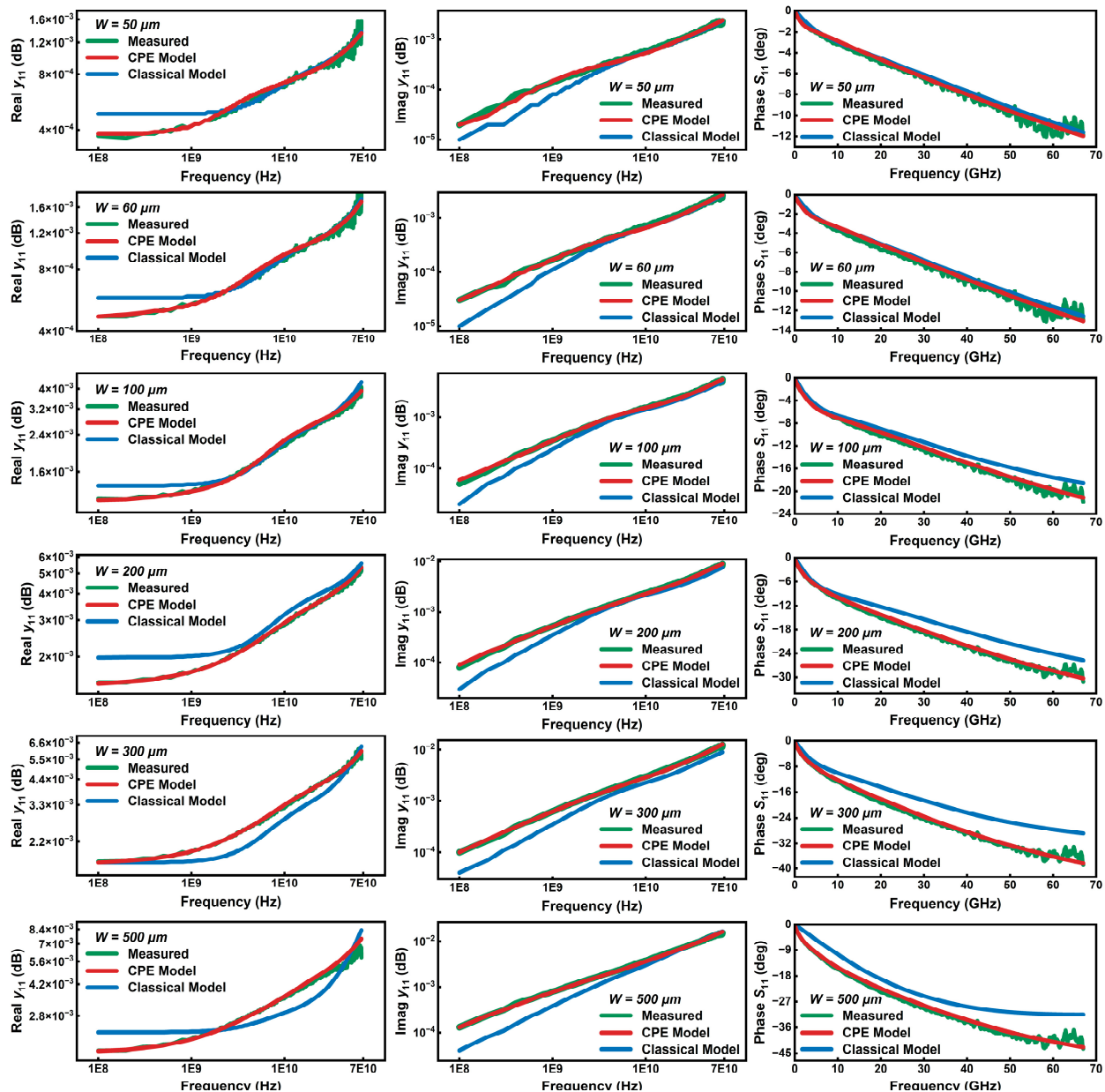


Figure 6. Comparison of S-parameters obtained from measurement, classical model, and CPE-based model for ACNT-SBDs with different channel widths under zero bias voltages.

Interestingly, the power-law exponent n increases from 0.59 to 0.78 as the channel width increases, indicating that the frequency response gradually approaches that of an ideal capacitor. This behavior suggests that, in larger ACNT-SBDs, the collective response of a greater number of nanotubes leads to a statistical averaging effect. In narrower devices, the small number of participating nanotubes makes the admittance more sensitive to local interfacial nonuniformities and trap-dominated processes, resulting in stronger dispersive behavior and lower n values. As the device area increases, the distributed variations are effectively averaged over the nanotube ensemble, smoothing extreme dispersive contributions and bringing the phase behavior closer to ideal capacitive response.

Therefore, the observed size dependence of Q and n reflects ensemble averaging and structural homogenization effects rather than increased dispersion. This evolution further supports the physical consistency of the CPE-based modeling framework for describing junction charge dynamics in ACNT-SBDs across different dimensions.

3.3. ACNT-SBDs for Third-Harmonic Frequency Multiplication

Building on the junction charge dynamics identified in the small-signal analysis, which constrain the high-frequency response of the Schottky junction, we further investigate the large-signal nonlinear behavior of ACNT-SBDs in the mmWave frequencies, with a focus on their practical performance in third-harmonic generation. All results presented in this section are obtained from direct measurements, without relying on circuit-level harmonic balance fitting, thereby preserving the intrinsic nonlinear response of the devices.

When a single-tone sinusoidal voltage excitation is applied to a Schottky diode, the nonlinear current–voltage relationship, defined as

$$v(t) = V_0 \cos(\omega_0 t), \quad (3)$$

can be expanded around the static operating point using a Taylor series:

$$i(v) = a_1 v + a_2 v^2 + a_3 v^3 + \dots \quad (4)$$

In such an expansion, the second-order nonlinear term mainly contributes to the DC and second-harmonic components, while the third-order term directly gives rise to the third-harmonic component:

$$i_{3\omega_0}(t) \propto a_3 V_0^3 \cos(3\omega_0 t). \quad (5)$$

An anti-parallel ACNT-SBD pair configuration was adopted in this work. In this structure, the two diodes exhibit odd-symmetric nonlinear characteristics under opposite voltage polarities, leading to cancellation of even-order harmonic currents, while third- and higher-order odd harmonics add constructively. As a result, selective enhancement of the third-harmonic component and effective suppression of even-order harmonics are achieved at the device level.

Third-harmonic measurements were carried out using an anti-parallel ACNT-SBD pair with a channel width of 60 μm , as shown in Figure 7a. To evaluate the intrinsic frequency multiplication capability under non-optimized conditions, no input or output impedance matching networks were introduced during the measurements. The fundamental signal was directly supplied by a mmWave signal generator, and the output harmonic power was monitored using a power meter. The harmonic measurements were conducted with an input power of 10 dBm. All measurements were performed under zero DC bias conditions. To ensure the accuracy of the measured power levels, a systematic calibration of the input power was conducted prior to the measurements, followed by independent evaluation of the transmission line and measurement system losses in the output path. The reported fundamental and third-harmonic output powers are therefore corrected based on these calibrations, representing the actual power levels at the device terminals.

Figure 7b shows the measured output power under an input power of 13 dBm and an input frequency of 10 GHz. Multiple harmonic components can be clearly observed. The output power at the fundamental frequency $f_0 = 10$ GHz remains relatively high, indicating good high-frequency conduction and signal transmission capability of the anti-parallel ACNT-SBD structure. More importantly, a pronounced third-harmonic component is observed at $3f_0 = 30$ GHz with an output power of -22.58 dBm. The second-harmonic component at $2f_0 = 20$ GHz exhibits an output power of -34.1 dBm, corresponding to a suppression ratio of 11.52 dB relative to the third harmonic. This result directly confirms the effectiveness of the anti-parallel configuration in suppressing even-order harmonics and selectively enhancing the third-harmonic component, in good agreement with the nonlinear theoretical analysis discussed above. When the input frequency is further increased to

13 GHz, as shown in Figure 7c, a similar harmonic distribution is maintained. The third-harmonic component at $3f_0 = 39$ GHz remains clearly observable with an output power of -25.01 dBm. At $2f_0 = 26$ GHz, the measured output power is -43.57 dBm, yielding a suppression ratio of 18.56 dB relative to the third harmonic. To evaluate the potential improvement in practical applications, additional circuit-level simulations incorporating optimized input and output impedance matching networks were performed. The simulation results indicate that, under conjugate matching conditions, the third-harmonic output power can be enhanced to -5.38 dBm at $3f_0 = 30$ GHz and -9.12 dBm at $3f_0 = 39$ GHz. These improvements correspond to a substantial increase in conversion efficiency compared with the unmatched configuration. This behavior indicates that the harmonic selection and suppression capability of the device is not limited to a single operating frequency, but is preserved across multiple mmWave bands. This observation further supports the relevance of the high cutoff frequency extracted from small-signal characterization to large-signal nonlinear operation. In addition to high-frequency performance, thermal stability and power-handling capability are important considerations for practical implementation. In the present study, harmonic measurements were conducted at an input power of 10 dBm, and no abnormal performance degradation or instability was observed during repeated measurements. Furthermore, the zero-bias operation mode reduces static power dissipation, which is beneficial for thermal management in compact RF front-end modules.

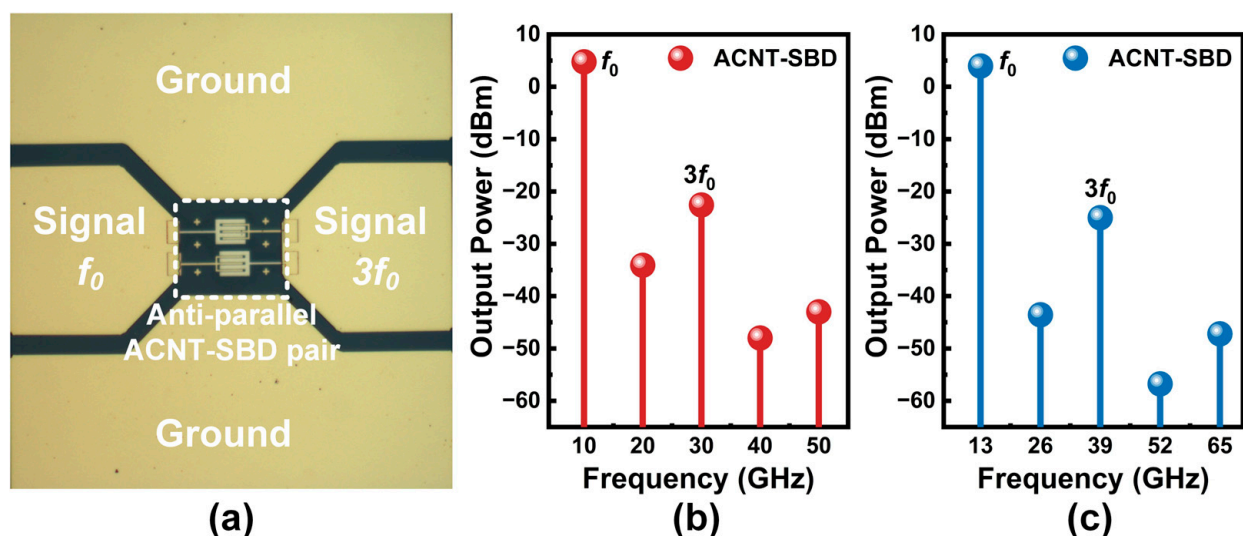


Figure 7. (a) Optical micrograph of the anti-parallel ACNT-SBD pair integrated with GSG pads; (b) Measured output power spectrum showing multiple harmonic components under an input frequency of 10 GHz; (c) Measured output power spectrum showing multiple harmonic components under an input frequency of 13 GHz.

4. Conclusions

In conclusion, this work presents a systematic experimental investigation of ACNT-SBDs, covering device fabrication, DC and RF characterization, small-signal modeling, and large-signal nonlinear measurements. ACNT-SBDs with a fixed electrode spacing and channel widths ranging from 50 to 500 μm were fabricated and evaluated. The devices exhibit clear Schottky rectifying behavior and pronounced size-dependent electrical characteristics. Notably, the device with a channel width of 500 μm achieves an intrinsic cutoff frequency of up to 282 GHz, demonstrating the strong high-frequency potential of ACNT-SBDs.

Based on measured S-parameters, a refined small-signal equivalent circuit model was developed to describe the high-frequency response of the ACNT-SBDs. Compared

with the classical RC-based model, the proposed model incorporating a parallel Rd–CPE branch provides significantly improved agreement with the measured Y-parameters and phase response over a broad frequency range and across different device dimensions. The systematic increase in the extracted CPE parameters Q and n with channel width further confirms that these dispersive effects naturally arise from the increased participation of carbon nanotubes and interface-related charge processes in larger devices.

The large-signal nonlinear characteristics of ACNT-SBDs were experimentally examined through third-harmonic generation. Without employing impedance matching or circuit-level optimization, the anti-parallel ACNT-SBD pair configuration exhibits effective suppression of even-order harmonics and a clear third-harmonic output. In particular, an output power of -22.58 dBm is obtained at $3f_0 = 30$ GHz under zero-bias operation.

Overall, this work provides a comprehensive experimental and modeling framework for evaluating the high-frequency and nonlinear characteristics of ACNT-SBDs and offers practical guidance for their further development in mmWave and nonlinear RF applications.

From a system-integration perspective, the demonstrated zero-bias operation, geometry scalability, and compact small-signal modeling framework make ACNT-SBDs promising candidates for hybrid integration with CMOS-based RF front-end architectures. In particular, the bias-dependent yet geometry-scalable model developed in this work facilitates circuit-level co-design with conventional silicon platforms. Moreover, the ACNT array structure enables wafer-scale transfer and heterogeneous integration onto pre-fabricated CMOS or RF substrates, which is compatible with emerging hybrid integration strategies combining low-dimensional materials with mature silicon technologies. These features position ACNT-SBDs as viable nonlinear building blocks for next-generation mmWave and THz front-end systems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16041873/s1>, Figure S1: Comparison of S-parameters obtained from measurement, classical model, and CPE-based model for ACNT-SBDs with different channel widths under 0.4 V bias.

Author Contributions: Conceptualization, H.L. and L.D.; methodology, H.L. and L.D.; validation, L.D. and J.W.; formal analysis, L.D.; investigation, L.D.; resources, H.L.; data curation, L.D. and J.W.; writing—original draft preparation, L.D.; writing—review and editing, L.D. and H.L.; supervision, H.L.; project administration, H.L.; funding acquisition, H.L. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SBD	Schottky barrier diodes (SBDs)
I	current
V	voltage
CNT	carbon nanotube
RF	radio-frequency
mmWave	millimeter-wave
DC	direct-current
f_c	cutoff frequency
R	resistor

C	capacitor
GSG	ground–signal–ground
EBE	electron-beam evaporation
Ti	titanium
Au	gold
SEM	scanning electron microscopy
DLSA	dimension-limited self-alignment
EBL	electron-beam lithography
Pd	palladium
R_s	contact resistance
C_j	junction capacitance
C_s	ohmic capacitance
R_d	coupling resistance
CPE	constant phase element

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