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978-1-107-12068-6 — Measurement Techniques for Radio Frequency Nanoelectronics
T. Mitch Wallis , Pavel Kabos
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1 An Introduction to Radio Frequency Nanoelectronics

1.1 Radio Frequency Nanoelectronics

The field of radio frequency (RF) nanoelectronics focuses on the fundamental study and engineering of devices that are enabled by nanotechnology and operate within a frequency range from about 100 MHz to about 100 GHz. This range includes frequencies traditionally identified as "radio frequencies," as well as microwaves and, at the high end of the frequency range, millimeter-waves. This emerging field sits at the intersection of two commercially vital trends in technology. The first trend is the ongoing shrinking of electronics to smaller length scales. Though this trend was initiated by the semiconductor and storage industries' pursuit of Moore's Law, the discoveries that followed have influenced a wide range of disciplines in addition to electronics, such as biological sensing, nanoelectromechanical systems, and low-dimensional materials science. The second overarching trend is the ever-increasing presence of devices that operate at radio frequencies, which has arisen in conjunction with the explosion of wireless connectivity. For the foreseeable future, communications technology will rely heavily on microwave and millimeter-wave transmission and in turn, devices that transmit, receive, and process signals at corresponding frequencies. In addition, current and foreseeable operating frequencies of integrated semiconductor electronics lie in the microwave frequency range. The ultimate goal of RF nanoelectronics is to leverage the new materials and new phenomena that have been revealed by scaling down to the nanoscale world in order to investigate new RF devices that will be of interest both for fundamental study and eventual commercial application.

In the past few decades, the emergence and growth of nanotechnology has proceeded hand in hand with the discovery and investigation of new forms of matter. Examples of nanoscale material systems, spanning from atomically thin two-dimensional materials to semiconducting nanowires to individual atoms, are shown in Fig. 1.1. From the outset, nanomaterials based on carbon have played a particularly important role. Indeed, one of the seminal moments in the brief history of nanotechnology was the synthesis of Buckminsterfullerenes in 1985 [1]. This achievement ignited the vigorous investigation of additional carbon-based nanomaterials, particularly graphene and carbon nanotubes (CNTs), which continues today [2]. Graphene is a stable, one-atom-thick sheet of carbon, while a

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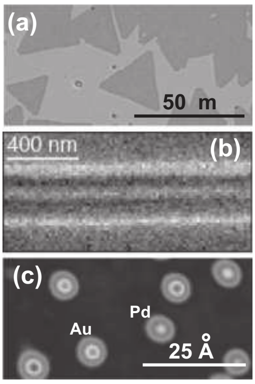

Figure 1.1. Nanomaterial systems.
(a) Optical microscope image of triangular shaped MoS_2 flakes. (Optical image courtesy of Prof. Xiaobo Yin, University of Colorado, Boulder.) (b) Near-field scanning microwave microscope image of a GaN nanowire. (c) Scanning tunneling microscope image of individual Pd and Au atoms. (STM image courtesy of Prof. Wilson Ho, University of California, Irvine.)

single-walled CNT may be conceptually understood as a ribbon of graphene that has been rolled into a tube. These materials have remarkable mechanical, electrical, and thermal properties. Furthermore, by altering the geometry of the constituent carbon atoms in fullerenes and CNTs, one can tune their particular material properties. While these carbon-based materials were initially seen as exotic, it's important to notice that the chemistry of carbon bonds naturally leads to these morphologies. In the words of Nobel laureate Richard Smalley, "Carbon has this genius of making a chemically stable two-dimensional, one-atom-thick membrane in a three-dimensional world" [3]. It was only with the development of nanoscale fabrication and measurement techniques that we were able to recognize these previously unseen materials.

Among the remarkable properties of CNTs and graphene, their capacity for high current densities is particularly appealing for RF nanoelectronic applications. One illustrative example of the potential application of these materials is the use of CNTs as interconnects in RF electronics. While copper has historically been the material of choice for electronic interconnects due to its low resistivity, the resistivity of copper increases due to surface scattering effects at dimensions lower than 100 nm [4]. In fact, the resistivity of a copper nanowire with a diameter of 60 nm is about ten times higher than the resistivity of bulk copper [5]. In contrast, the properties of metallic, single-walled CNTs are superior to copper nanowires in many ways. Conduction of electrons in metallic CNTs is ballistic, leading to current densities greater than 10^9 A/cm^2 and electron mean free paths greater than 10^3 nm [6]. For copper, the corresponding values are three and two orders of magnitude smaller, respectively. As a result, CNTs are promising candidates for low-loss interconnects operating at gigahertz frequencies. Recently, integrated circuits have been

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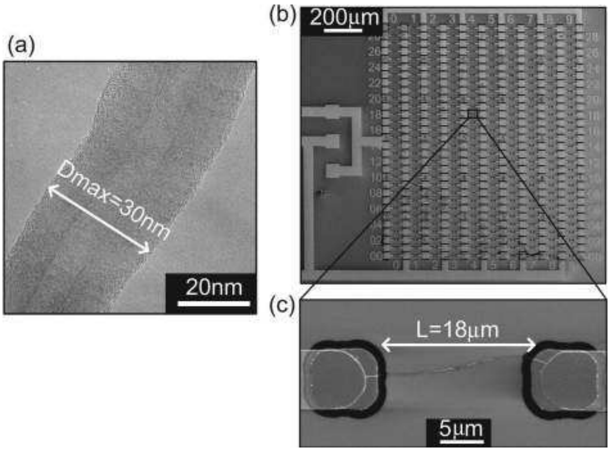

Figure 1.2. Multiwalled CNT interconnects.
(a) Transmission electron microscope image of a 30 nm multiwalled CNT. (b) Scanning electron microscope image of an array of multiwalled CNT interconnects. (c) Scanning electron microscope image of an individual interconnect. © 2009 IEEE. Reprinted, with permission from G. F. Close, S. Yasuda, B. Paul, S. Fujita, and H.-S. P. Wong, *IEEE Transactions on Electron Devices* 56 (2009) pp. 43–49.

demonstrated that combine silicon complementary-metal-oxide-semiconductor (CMOS) transistors with individual multiwalled CNT interconnects operating at one gigahertz [7], [8], as shown in Fig. 1.2.

Beyond the families of carbon-based materials, the palette of materials utilized in nanotechnology is wide, varied, and ever-expanding. Two-dimensional, graphene-like materials such as transition metal dichalcogenides (TMDs), though atomically thin, can extend to microscopic or even macroscopic lateral dimensions [9]. Nanowires have been grown for many types of materials, finding applications not only in RF nanoelectronics [10], but also in ultrasensitive, low-power sensing [11] and optoelectronics [12]. At the spatial limit, individual molecules and atoms represent the ultimate nanoscale material system. One of the central concepts of nanotechnology in general and nanoelectronics in particular is that these individual nanoscale material systems can serve as building blocks, from which complex devices with novel functionalities may be assembled. As examples, one can imagine multilayered stacks of two-dimensional materials or ensembles of molecules organized via self-assembly as customized material systems whose properties may be tuned and engineered.

While new material systems are one of the hallmarks of modern nanotechnology, they are not sufficient in and of themselves to distinguish nanoscience from other disciplines. Indeed, long before the term “nanotechnology” was coined, chemists were synthesizing new molecules and solid state physicists were engineering microelectronic devices by assembling semiconductor materials and components. One extraordinary feature of nanotechnology that distinguishes it from such earlier endeavors is access to and control of individual nanoscale building blocks. In order for RF nanoelectronic devices to be realized, individual nanoscale components must be placed in precise arrangements and individual elements must be addressable via high-quality electrical contacts. As a result of recent advances, many examples now exist of such capability and control. It is now possible to align individual nanowires with electrical contacts by use of dielectrophoresis [13] or fabricate graphene nanoribbons with ion beams [14]. At even smaller length scales, mechanical break junctions make it possible to isolate and measure individual molecules [15], while scanning probe microscopes are able to fabricate, manipulate, and characterize nanostructures one atom at a time [16]. Furthermore, industrially scalable processes for materials synthesis and processing have emerged that will make nanodevice fabrication compatible with bulk manufacturing [17].

1.2 Measurement Problems in RF Nanoelectronics

While the synthesis of new nanomaterials and the control of nanoscale building blocks at the spatial limit are critical to realizing RF nanotechnology, the promise of RF nanoelectronic devices will only be realized with accurate measurement science. The ultimate application and commercialization of RF nanoelectronic devices requires reproducible measurements for optimization of performance and informed selection between competing designs. Furthermore, reliable, quantitative determination of measurement uncertainties is desirable throughout all stages of RF device engineering. At a more fundamental level, measurements are vital to developing and testing quantitative models of underlying physics. As fundamental discoveries lead to the development of devices, quantitative measurements provide necessary insights and feedback for evaluating innovative device concepts. Finally, in an emerging field such as RF nanoelectronics, measurements can serve as a means for finding a common framework of terminology, calibration, and standard benchmarking among different research efforts.

Considered separately, both RF device measurements and nanoscale measurements are extremely challenging fields. In the development of measurement techniques for RF nanoelectronics, we must build upon both of these branches of metrology, adapting existing techniques while also forging new methods. Such blending of techniques naturally leads to cross-pollination of traditionally separate disciplines. This multidisciplinary nature of nanotechnology is part of what makes the field exciting. However, when trained specialists cross into unfamiliar disciplines, there is always some risk of misunderstanding. For many individuals who come to the field of RF nanoelectronics with minimal experience in RF and microwave measurements, there is much to learn about the art of microwave engineering in general and that of microwave measurements in particular. Conversely, those who have mastered microwave measurements, but have minimal experience in nanoscale measurements, have much to learn about material fabrication and workhorse characterization techniques such as scanning probe microscopy and spectroscopy.

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Historically, progress in nanoscience and nanotechnology research has proceeded in step with progress in nanoscale measurement science. For example, the inventions of scanning tunneling microscopy [18] and atomic force microscopy [19] have enabled the visualization and characterization of surfaces with atomic-scale resolution. Electron microscopy techniques such as transmission electron microscopy and scanning electron microscopy also continue to reveal the beauty and complexity of matter at length scales from micrometers down to Ångstroms. Moreover, as such measurement tools have matured, they have become more versatile, providing chemical sensitivity, electronic and vibrational spectroscopic capabilities, as well as nanomanipulation and nanofabrication capabilities. With this versatility has come a breadth of application areas and specialized measurement modes.

The historical development of microwave measurements has also led to the emergence of a substantial number of subdisciplines, including measurements of noise, power, and impedance, as well as antenna characterization and other free space measurement techniques. The subdisciplines that are most relevant to RF nanoelectronics relate to the measurement of complex scattering parameters in guided-wave systems, such as waveguides and coaxial transmission lines [20]. Also, measurements of RF nanoelectronic devices rely heavily on the extension of techniques for on-wafer measurement of scattering parameters. For all guided-wave measurements, the development of the six-port reflectometer was an important milestone, paving the way for contemporary vector network analyzers, which are critical tools for nearly all of the measurement methods that are discussed in this book.

In the previous section, the application of CNTs as RF interconnects was presented as an illustrative example of a promising application of RF nanoelectronics. This example also illustrates how advances in measurement science are required in order for such applications to be realized. The recent development of microwave metrology for CNTs in general [21], [22], and CNT interconnects in particular [23], has revealed a number of substantial measurement challenges. How can microwave measurements be extended to systems with extremely high impedance? How can the intrinsic RF properties of nanoscale building blocks such as CNTs be de-embedded from contact impedance, parasitic capacitance, and other properties of the host device? Further, once de-embedding is possible, how can physical properties of the nanoscale components be estimated from the microwave measurements? Finally, what are the uncertainties in these measurements? In an effort to answer such questions, the research and development of RF nanoelectronic systems has necessarily led to the development of new measurement methods, which continues as the field extends to new materials, new length scales, new modeling approaches, and new frequencies.

1.3 Measurement Techniques for RF Nanoelectronics

The initial measurement techniques that were developed for RF nanoelectronics extended guided-wave microwave measurement techniques to devices and circuits

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that incorporated nanoscale building blocks [21], [24]–[27]. The measurands for these techniques are the frequency-dependent, complex scattering parameters. In general, these techniques require calibration approaches that allow the scattering parameters of the device under test (DUT) to be de-embedded from the effects of the test equipment. A further requirement for many RF nanoelectronic DUTs is that the technique must account for the extreme impedance mismatch between the nanoelectronic DUT and the test equipment. In many instances, a further objective is to use modeling and simulation to extract intrinsic properties of the nanoscale components in a measured device, as well as circuit parameters of interest such as contact impedance and other sources of parasitic reactance.

In this book, Chapters 2 through 6 describe several approaches to the extension of established guided-wave measurement techniques to RF nanoelectronic DUTs. First, Chapter 2 reviews the core concepts of guided-wave measurements techniques. Chapter 3 adapts these techniques to the general case of extreme impedance DUTs while Chapter 4 narrows the focus to on-wafer measurements of RF nanoelectronics. Chapter 5 covers modeling and simulation of RF nanoelectronics with emphasis on validation and circuit parameter extraction. In general, many aspects of RF nanoelectronic device development, including simulation, fabrication, and measurement, are difficult. As a result, a reliable framework for broadband characterization of nanoscale components necessarily incorporates multiple aspects such as specially fabricated test structures, calibration techniques, and validation through numerical simulation. To illustrate this multifaceted characterization strategy, Chapter 6 describes a case study that highlights strategies and challenges related to implementing a specific RF nanoelectronic device measurement, namely the broadband measurement of a two-port, on-wafer GaN nanowire device.

Beyond global device characterization, there is a need for approaches that provide microwave measurements that are spatially localized within a device, providing insight into the impacts of defects, interfaces, and other localized features upon device performance. In addition to intra-device measurement capabilities, it is also highly desirable to make nondestructive, RF measurements of the intrinsic properties of individual building blocks in a contact-free environment. One effective approach to both these measurement problems is to combine the nanometer-scale spatial resolution of scanning probe microscopy with broadband sensitivity in the frequency range from 100 MHz to 100 GHz. This combination can be realized by the integration of a one-port microwave network into the signal path of a scanning probe instrument, such as an atomic force microscope (AFM). In this book, we will refer to such an instrument as a “near-field scanning microwave microscope” (NSMM), but there are a number of closely related techniques that are described in the literature, including scanning capacitance microscopy and scanning impedance microscopy. An example of an NSMM [28] is shown in Fig. 1.3. As in other scanning probe microscope systems, NSMM requires that a probe be positioned on the order of a nanometer above a sample surface. A distance-following feedback mechanism is required to maintain a precise tip-sample separation as the probe tip is rastered across the sample surface.

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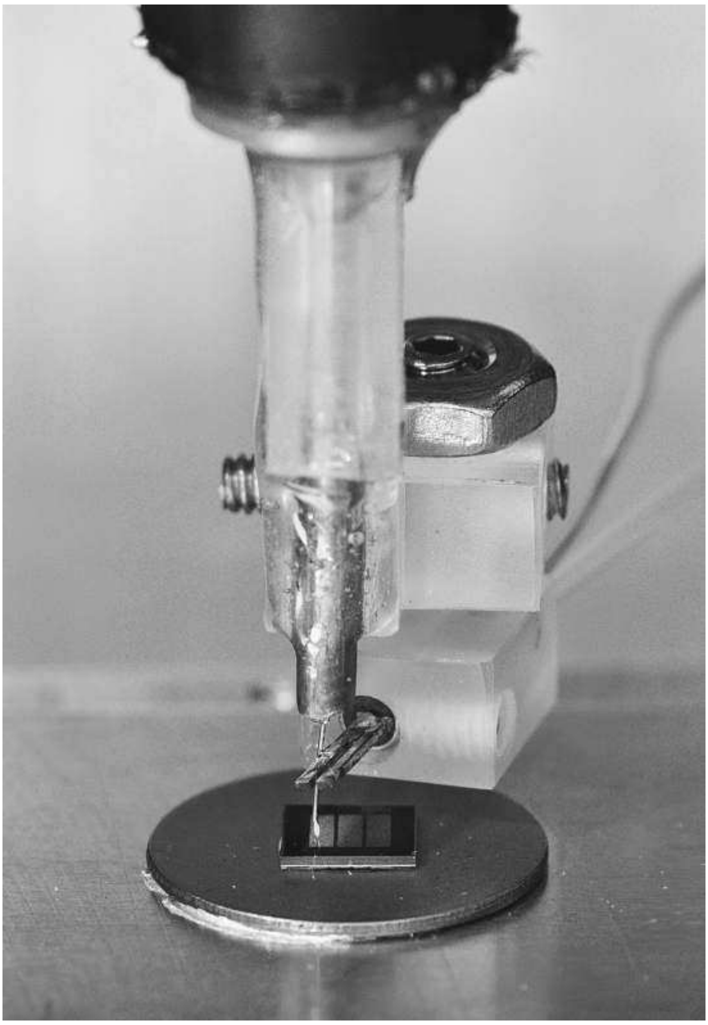

Figure 1.3. Near-field scanning microwave microscope (NSMM).
This photograph shows one of many different possible implementations of an NSMM. The system shown here has a needle-shaped probe extending from a truncated coaxial cable and uses a tuning-fork-based feedback system for distance following. Further details can be found in Reference [28]. Photograph by C. Suplee, NIST.

Ultimately, the outputs of NSMM and related techniques include high-resolution images and spatially localized spectroscopic measurements. Measurands include local impedance, capacitance, dopant concentration, sheet resistance, complex permittivity, and complex permeability. Further development of systems with multiple probes offers the opportunity to measure intra-device and intra-material transport as well as RF coupling between separated nanoscale components. Finally, the microwave skin depth effect enables an NSMM to measure subsurface electronic properties of materials and devices.

NSMM techniques are covered in Chapters 7 through 9. In Chapter 7, NSMM instrumentation is reviewed and a variety of different NSMM implementations are compared and contrasted. Chapter 8 presents a model of the tip-sample interaction in an NSMM. Building upon that model, the chapter also presents strategies for extracting calibrated, quantitative measurements, such as absolute capacitance measurements, from NSMM data. Chapter 9 introduces the fundamental concepts of electromagnetic materials measurements, then narrows its focus to a review of applications of NSMM to materials measurements.

Advances in nanoscience and nanotechnology have impacted many research and application areas across multiple disciplines, including nanoelectronics, optoelectronics, and biomedicine. Similarly, the measurement techniques developed for RF nanoelectronics have found applications in many fields. Thus, the final five chapters of the book cover specific measurement problems that are of ongoing interest. These areas serve as practical examples of how the measurement techniques for RF nanoelectronics are extended and customized for specific problems and applications. Chapter 10 discusses the broadband characterization of active nanotransistor devices in the RF range, including approaches for de-embedding intrinsic device properties from measurements. Chapter 11 presents approaches to spatially resolved dopant profiling of semiconductors by use of NSMM and related techniques. Subsurface measurements made by use of NSMM are then covered in Chapter 12. The subsurface imaging capability of NSMM is an emerging field of metrology that takes advantage of the microwave skin depth effect, thus providing a nondestructive approach to the characterization of subsurface interfaces and defects. However, quantitative subsurface measurements require complex mathematical approaches to inverse problems. Chapter 13 discusses measurements of nanoscale magnetic systems. The natural time scale for the dynamics of nanomagnetic systems falls in the microwave regime, providing an opportunity for the application and adaptation of measurements developed for RF nanoelectronics. Chapter 14 concludes with a discussion of nanoscale electromagnetic measurements for life science and medical applications.

References

[1] H. W. Kroto, J. R. Heath, S. C. O'Brien, R. F. Curl, and R. E. Smalley, "C60: Buckminsterfullerene," *Nature* 318 (1985) pp. 162–163.

[2] H.-S. P. Wong and D. Akinwande, *Carbon Nanotube and Graphene Device Physics* (Cambridge University Press, 2011).

[3] R. E. Smalley, "Discovering the Fullerenes," Nobel Lecture, December 7, 1996.

[4] W. Steinhogl, G. Schindler, G. Steinlesberger, M. Traving, and M. Engelhardt, "Comprehensive Study of the Resistivity of Copper Wires with Lateral Dimensions of 100 nm and Smaller," *Journal of Applied Physics* 97 (2005) art. no. 023706.

[5] M. E. Toimil Molares, E. M. Hohberger, C. Schaeflein, R. H. Blick, R. Neumann, and C. Trautmann, "Electrical Characterization of Electrochemically Grown Single Copper Nanowires," *Applied Physics Letters* 82 (2003) pp. 2139–2141.

[6] A. Javey, P. Qi, Q. Wang, and H. Dai, "Ten- to 50-nm-long Quasi-Ballistic Carbon Nanotube Devices Obtained without Complex Lithography," *Proceedings of the National Academy of Sciences of the United States of America* 101 (2004) pp. 13408–13410.

[7] G. F. Close, S. Yasuda, B. Paul, S. Fujita, and H.-S. P. Wong, "A 1 GHz Integrated Circuit with Carbon Nanotube Interconnects and Silicon Transistors," *Nano Letters* 8 (2008) pp. 706–709.

[8] G. F. Close, S. Yasuda, B. Paul, S. Fujita, and H.-S. P. Wong, "Measurement of Subnanosecond Delay through Multiwall Carbon-Nanotube Local Interconnects on a CMOS Integrated Circuit," *IEEE Transactions on Electron Devices* 56 (2009) pp. 43–49.

[9] G. Fiori, F. Bonaccorso, G. Iannaccone, T. Palacios, D. Nuemaier, A. Seabaugh, S. K. Banerjee, and L. Colombo, "Electronics Based on Two-Dimensional Materials," *Nature Nanotechnology* 9 (2014) pp. 768–779.

[10] X. Miao, K. Chabak, C. Zhang, P. K. Mohseni, D. Walker, and X. Li, "High-Speed Planar GaAs Nanowire Arrays with $f_{max} > 75$ GHz by Wafer-Scale Bottom-Up Growth," *Nano Letters* 15 (2015) pp. 2780–2786.

[11] F. Gu, L. Zhang, X. Yin, and L. Tong, "Polymer Single-Nanowire Optical Sensors," *Nano Letters* 8 (2008) pp. 2757–2761.

[12] X. Duan, Y. Huang, Y. Cui, J. Wang, and C. M. Lieber, "Indium Phosphide Nanowires as Building Blocks for Nanoscale Electronic and Optoelectronic Devices," *Nature* 409 (2001) pp. 66–69.

[13] A. Motayed, M. He, A. V. Davydov, J. Melngailis, and S. N. Mohammad, "Realization of Reliable GaN Nanowire Transistors Utilizing Dielectrophoretic Alignment Technique," *Journal of Applied Physics* 100 (2006) art. no. 114310.

[14] J.-F. Dayen, A. Mahmood, D. S. Golubev, I. Roch-Jeune, P. Salles, and E. Dujardin, "Side-Gated Transport in Focused-Ion-Beam-Fabricated Multilayered Graphene Nanoribbons," *Small* 4 (2008) pp. 716–720.

[15] D. Natelson, "Mechanical Break Junctions: Enormous Information in a Nanoscale Package," *ACS Nano* 6 (2012) pp. 2871–2876.

[16] W. Ho, "Single-Molecule Chemistry," *Journal of Chemical Physics* 117 (2002) pp. 11033–11061.

[17] N. Behabtu, C. C. Young, D. E. Tsentalovich, O. Kleinerman, X. Wang, A. W. K. Ma, E. A. Bengio, R. F. ter Waarbeek, J. J. de Jong, R. E. Hoogerwerf, S. B. Fairchild, J. B. Ferguson, B. Maruyama, J. Kono, Y. Talmon, Y. Cohen, M. J. Otto, and M. Pasquali, "Strong, Light, Multifunctional Fibers of Carbon Nanotubes with Ultrahigh Conductivity," *Science* 339 (2013) pp. 182–186.

[18] G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, "Surface Studies by Scanning Tunneling Microscopy," *Physical Review Letters* 49 (1982) pp. 57–61.

[19] G. Binnig, C. F. Quate, and Ch. Gerber, "Atomic Force Microscope," *Physical Review Letters* 56 (1986) pp. 930–933.

[20] V. Teppati, A. Ferrero, and M. Sayed (Eds.), *Modern RF and Microwave Measurement Techniques* (Cambridge University Press, 2013).

[21] J. J. Plombon, K. P. O'Brien, F. Gstrein, V. M. Dubin, and Y. Jiao, "High Frequency Electrical Properties of Individual and Bundled Carbon Nanotubes," *Applied Physics Letters* 90 (2007) art. no. 063106.

[22] P. Rice, T. M. Wallis, S. E. Russek, and P. Kabos, "Broadband Electrical Characterization of Multiwalled Carbon Nanotubes and Contacts," *Nano Letters* 7 (2007) pp. 1086–1090.

[23] L. Hao, D. Cox, K. Lees, J. C. Gallop, P. See, R. Clarke, T. J. B. M. Janssen, R. F. Zhang, and F. Wei, "Fabrication and Characterization of Carbon Nanotubes as r.f.

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Excerpt
More Information

Interconnects,” *2012 12th IEEE Conference on Nanotechnology (IEEE NANO)* (2012) pp. 1–5.

[24] S. Li, Z. Yu, S.-F. Yen, W. C. Tang, and P. J. Burke, “Carbon Nanotube Transistor Operation at 2.6 GHz,” *Nano Letters* 4 (2004) pp. 753–756.

[25] J. M. Bethoux, H. Happy, G. Dambrine, V. Derycke, M. Goffman, and J. P. Burgoin, “An 8-GHz f_t Carbon Nanotube Field-Effect Transistor for Gigahertz Range Applications,” *IEEE Electron Device Letters* 27 (2006) pp. 681–683.

[26] S. Vandenbrouck, K. Madjour, D. Theon, Y. Dong, Y. Li, C. M. Lieber, and C. Gaquiere, “12 GHz F_{MAX} GaN/AlN/AlGaN Nanowire MISFET,” *IEEE Electron Device Letters* 30 (2009) pp. 322–324.

[27] T. Wang, K. Jeppson, N. Olofsson, E. E. B. Campbell, and J. Liu, “Through Silicon Vias Filled with Planarized Carbon Nanotube Bundles,” *Nanotechnology* 20 (2009) art. no. 485203.

[28] J. C. Weber, J. B. Schlager, N. A. Sanford, A. Imtiaz, T. M. Wallis, L. M. Mansfield, K. J. Coakley, K. A. Bertness, P. Kabos, and V. M. Bright, “A Near-Field Scanning Microwave Microscope for Characterization of Inhomogeneous Photovoltaics,” *Review of Scientific Instruments* 83 (2012) art. no. 083702.