Chapter 12
Conclusions and Outlook

Abstract The development of NW-based materials has led to breakthrough achievements with rapid expanding impact in all areas of nanotechnology, including but not limited to, electronics, optoelectronics, energy science, sensors and the life sciences. In spite of the progresses discussed in this book, substantial room still exists for NW research and development, and the opportunities may be realized by exquisite control of NW synthesis and assembly, as well as large scale production. In this chapter, we will summarize the basic NW research and applications introduced in this book, and challenges and exciting future opportunities will be discussed.

Central to the vision underlying nanotechnology is the idea that developing and following a common intellectual path—the bottom-up paradigm of nanoscale science and technology—will make it possible to build or assemble virtually any kind of device or functional system, ranging from ultrasensitive medical sensors to nanocomputers and brain-machine interfaces. Underpinning this bottom-up paradigm is the controlled growth of nanoscale materials—the building blocks of the bottom-up approach—pursued within the disciplines of materials sciences and chemistry. In this book we have reviewed the remarkable progress made over the past two plus decades in NW research developing this broad vision.

The intimate integration and interplay between growth and fundamental characterization has enabled the field not only to expand the basic understanding of NW science and technology, but also to make rational predictions and define new device concepts unique to these nanoscale building blocks. A key that has been and will continue to be critical to continued scientific advances is expanding the level of rational synthetic control of the powerful NW building blocks with precisely controlled and tunable chemical composition, structure, size, and morphology since these characteristics ultimately determine physical properties. Moreover, the capability to create new NW topologies and assemblies where composition and structure are tuned on multiple length scales has been and will continue to be central to scientific breakthroughs, such as the first demonstrations of intracellular transistors merging key elements of living and nonliving information processors [1–3], that can enable new and potentially transformative future technologies. In this

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regard, semiconductor NWs serve as one of the most powerful platform available today in nanoscience given that it is now possible to design structures ab initio, and synthetically realize these structures with the structure and composition controlled from the atomic scale and up. This capability to design and synthetically realize complex NW materials is almost unique among nanomaterials, and enables systems or building blocks to be created, which have predictable physical properties and which enable testing fundamental limits of performance [4–9].

To fully exploit this bottom-up paradigm in technologies, it will be important to also build upon rational methods of organizing NWs and other nanomaterials. The building blocks need to be assembled not only in close-packed arrays, which give a very fixed kind of interconnectivity, but the orientation, position and spacing controlled on multiple length scales [10]. It is also possible to assemble hybrid or multi-component functional materials in novel environments using diverse NW building blocks [11], allowing for rational exploration of new architectures and possible applications of multi-component material systems. In addition, advances described in this book have shown how this approach has already enabled new concepts for NW device structures, functional units and systems [12–15], and thus demonstrates unambiguously the potential of creating technologies that might previously have been more the realm of science fiction versus scientific reality.

Over the past two decades, research on NWs has witnessed fast developments, as well as substantial and robust achievements that are synonymous with original ideas put forth in seminal publications [16–18]; that is, the capability to synthetically-control composition, structure, morphology on multiple length scales allows for remarkable advances simply not possible in single component materials. The development of NW-based materials has led to breakthrough achievements with rapid expanding impact in all areas of nanotechnology. The remarkable performance properties of NWs are leading to revolutionary technologies in electronics, optoelectronics, energy science, sensors and the life sciences more generally, and will continue to broadly impact the fields of physics, chemistry, biology, medicine, environmental science, and engineering [19–32]. For example, in the energy studies, especially related to renewable energy conversion and storage, the rational design of SiNW structures and array architectures, together with surface coating and bandgap engineering, has demonstrated significant potentials in increasing light absorption, charge transfer and separation, photoconversion efficiencies, and chemical and catalytic performances [33–35]. In the biological studies, for instance, sensor devices based on SiNW-FETs are emerging as a general and powerful platform for ultrasensitive, direct electrical detection of biological and chemical species, as well as interfacing with live cells and tissues for nonconventional intracellular electrical measurements [9, 22, 23, 28, 29, 32]. The authors believe this latter area has tremendous growth potential from perspectives of both basic research and applications, and expect to see transformative advances impacting medicine and healthcare in the future.

In spite of the remarkable progress discussed in this book, substantial room still exists for basic NW research and development. These opportunities may be realized by tackling several challenges. First, the ultimate understanding and exquisite control of NW synthesis with atomic accuracy in material morphologies, structures, chemical modulations, and doping profiles, have not been fully realized by current synthetic methods and technologies. Second, the assembly and patterning of NWs into functional device arrays with higher efficiency, accuracy and uniformity will benefit exploration of larger scale integrated systems for research as well commercialization of existing NW devices that do exhibit unique properties, such as in the biological realm [36]. Third, development of efficient large scale NW synthesis/production is ultimately needed to fuel large-scale applications as well as efficient commercialization strategies to realize the most promising technologies. Looking into the future, continued efforts to exploit the unique capabilities that exist today in NW building blocks and will further expand with continued efforts, for example by thinking out of the box to applications not possible with existing planar technologies, promises to be a fruitful direction for creating new NW-based research tools, which may answer long-standing questions or even allow researchers to pose new questions with the advanced capabilities, to transformative and/or disruptive technologies for commercialization. We believe that the future is remarkably bright, with likely revolutionary technologies from NW-based nanosystems that will impact in many ways in areas such as life sciences, healthcare, information technology, and energy science, and importantly, in so doing offer a substantial benefit to humankind.

References

1. B. Tian, T. Cohen-Karni, Q. Qing, X. Duan, P. Xie, C.M. Lieber, Three-dimensional, flexible nanoscale field-effect transistors as localized bioprobes. Science **329**(5993), 830–834 (2010)
2. X. Duan, R. Gao, P. Xie, T. Cohen-Karni, Q. Qing, H.S. Choe, B. Tian, X. Jiang, C.M. Lieber, Intracellular recordings of action potentials by an extracellular nanoscale field-effect transistor. Nat. Nanotechnol. **7**(3), 174–179 (2012)
3. Q. Qing, Z. Jiang, L. Xu, R. Gao, L. Mai, C.M. Lieber, Free-standing kinked nanowire transistor probes for targeted intracellular recording in three dimensions. Nat. Nanotechnol. **9**, 142–147 (2014)
4. C.M. Lieber, Nanoscale science and technology: building a big future from small things. MRS Bull. **28**(07), 486–491 (2003)
5. X. Duan, C.M. Lieber, Semiconductor nanowires: rational synthesis, in *Dekker Encyclopedia of Nanoscience and Nanotechnology*, ed. by J.A. Schwarz (Marcel Dekker, Inc., New York, 2005)
6. W. Lu, C.M. Lieber, Semiconductor nanowires. J. Phys. D Appl. Phys. **39**(21), R387–R406 (2006)
7. C.M. Lieber, Z.L. Wang, Functional nanowires. MRS Bull. **32**(02), 99–108 (2007)
8. Z. Zhong, C. Yang, C.M. Lieber, Silicon nanowires and nanowire heterostructures, in *Nanosilicon*, ed. by V. Kumar (Elsevier, Amsterdam, 2008), pp. 176–216
9. C.M. Lieber, Semiconductor nanowires: a platform for nanoscience and nanotechnology. MRS Bull. **36**(12), 1052–1063 (2011)
10. J. Yao, H. Yan, C.M. Lieber, A nanoscale combing technique for the large-scale assembly of highly aligned nanowires. Nat. Nanotechnol. **8**(5), 329–335 (2013)
11. A. Javey, S. Nam, R.S. Friedman, H. Yan, C.M. Lieber, Layer-by-layer assembly of nanowires for three-dimensional, multifunctional electronics. Nano Lett. **7**(3), 773–777 (2007)

12. J. Yao, H. Yan, S. Das, J.F. Klemic, J.C. Ellenbogen, C.M. Lieber, Nanowire nanocomputer as a finite-state machine. Proc. Natl. Acad. Sci. USA **111**(7), 2431–2435 (2014)
13. W. Shim, J. Yao, C.M. Lieber, Programmable resistive-switch nanowire transistor logic circuits. Nano Lett. **14**(9), 5430–5436 (2014)
14. H. Yan, H.S. Choe, S. Nam, Y. Hu, S. Das, J.F. Klemic, J.C. Ellenbogen, C.M. Lieber, Programmable nanowire circuits for nanoprocessors. Nature **470**(7333), 240–244 (2011)
15. Y. Dong, G. Yu, M.C. McAlpine, W. Lu, C.M. Lieber, Si/a-Si core/shell nanowires as nonvolatile crossbar switches. Nano Lett. **8**(2), 386–391 (2008)
16. H. Dai, E.W. Wong, Y.Z. Lu, S. Fan, C.M. Lieber, Synthesis and characterization of carbide nanorods. Nature **375**(6534), 769–772 (1995)
17. C. Lieber, A. Morales, P. Sheehan, E. Wong, P. Yang, in *One-Dimensional Nanostructures: Rational Synthesis, Novel Properties and Applications*. Proceedings of the Robert A. Welch Foundation 40th Conference on Chemical Research: Chemistry on the Nanometer Scale (1997), pp. 165–187
18. A.M. Morales, C.M. Lieber, A laser ablation method for the synthesis of crystalline semiconductor nanowires. Science **279**(5348), 208–211 (1998)
19. Y. Huang, X. Duan, C.M. Lieber, Semiconductor nanowires: nanoscale electronics and optoelectronics, in *Dekker Encyclopedia of Nanoscience and Nanotechnology*, ed. by J.A. Schwarz (Marcel Dekker, Inc., New York, 2005)
20. R. Agarwal, C.M. Lieber, Semiconductor nanowires: optics and optoelectronics. Appl. Phys. A **85**(3), 209–215 (2006)
21. Y. Li, F. Qian, J. Xiang, C.M. Lieber, Nanowire electronic and optoelectronic devices. Mater. Today **9**(10), 18–27 (2006)
22. F. Patolsky, G. Zheng, C.M. Lieber, Nanowire sensors for medicine and the life sciences. Nanomedicine **1**, 55–65 (2006)
23. F. Patolsky, B.P. Timko, G. Zheng, C.M. Lieber, Nanowire-based nanoelectronic devices in the life sciences. MRS Bull. **32**(02), 142–149 (2007)
24. W. Lu, P. Xie, C.M. Lieber, Nanowire transistor performance limits and applications. IEEE T. Electron. Dev. **55**(11), 2859–2876 (2008)
25. B. Tian, T.J. Kempa, C.M. Lieber, Single nanowire photovoltaics. Chem. Soc. Rev. **38**(1), 16–24 (2009)
26. B. Tian, C.M. Lieber, Design, synthesis, and characterization of novel nanowire structures for photovoltaics and intracellular probes. Pure Appl. Chem. **83**(12), 2153 (2011)
27. T. Cohen-Karni, C.M. Lieber, Nanowire nanoelectronics: building interfaces with tissue and cells at the natural scale of biology. Pure Appl. Chem. **85**(5) (2013)
28. X. Duan, T.-M. Fu, J. Liu, C.M. Lieber, Nanoelectronics-biology frontier: from nanoscopic probes for action potential recording in live cells to three-dimensional cyborg tissues. Nano Today **8**(4), 351–373 (2013)
29. X. Duan, C.M. Lieber, Nanoelectronics meets biology: from new nanoscale devices for live-cell recording to 3D innervated tissues. Chem. Asian J. **8**(10), 2304–2314 (2013)
30. X. Duan, C.M. Lieber, Nanoscience and the nano-bioelectronics frontier. Nano Res. **8**(1), 1–22 (2015)
31. P.B. Kruskal, Z. Jiang, T. Gao, C.M. Lieber, Beyond the patch clamp: nanotechnologies for intracellular recording. Neuron **86**(1), 21–24 (2015)
32. A. Zhang, C.M. Lieber, Nano-bioelectronics. Chem. Rev. **116**(1), 215–257 (2016)
33. Y. Wang, T. Wang, P. Da, M. Xu, H. Wu, G. Zheng, Silicon nanowires for biosensing, energy storage, and conversion. Adv. Mater. **25**(37), 5177–5195 (2013)
34. K.-Q. Peng, X. Wang, L. Li, Y. Hu, S.-T. Lee, Silicon nanowires for advanced energy conversion and storage. Nano Today **8**(1), 75–97 (2013)
35. A.I. Hochbaum, P. Yang, Semiconductor nanowires for energy conversion. Chem. Rev. **110**(1), 527–546 (2010)
36. G. Yu, C.M. Lieber, Assembly and integration of semiconductor nanowires for functional nanosystems. Pure Appl. Chem. **82**(12), 2295–2314 (2010)