Nanoscience and Nanotechnology in the Posthype Era

As noted by Dawn Bonnell in her November 2010 *ACS Nano* editorial,[1] a global study led by Dr. Mihail Roco, Senior Advisor for Nanotechnology at the National Science Foundation, has recently been completed in an effort to assess the past decade and project the next decade of nanoscience and nanotechnology research. The ~500 page report (frequently referred to as Nano2)[2] provides detailed information on several topics including theory/modeling/simulation, instrumentation/metrology, nanomanufacturing, environment/health/safety, sustainability, energy, medicine, nanoelectronics, nanomagnetics, nanophotonics/plasmonics, nanomaterials, education, and governance. In addition to assembling a wealth of examples, references, and perspectives, this study identifies a number of broader themes concerning the development of nanoscience and nanotechnology. This editorial will explore one of these themes related to the so-called "hype cycle" that has been experienced by the nanoscience and nanotechnology field.

The hype cycle is credited to Gartner Research and has been broadly applied to the maturity, adoption, and application of emerging technologies.[3] The hype cycle proceeds through five phases: (1) technology trigger; (2) peak of inflated expectations; (3) trough of disillusionment; (4) slope of enlightenment; and (5) plateau of productivity. In the context of nanoscience and nanotechnology, the technology trigger is explored in some detail by two earlier studies led by Dr. Mihail Roco,[4,5] ultimately culminating in the announcement of the U.S. National Nanotechnology Initiative (NNI) by President William Jefferson Clinton in 2000.

The peak of inflated expectations quickly followed. In fact, evidence for the inflated expectations can be found in President Clinton's 2000 State of the Union address: "Soon researchers will bring us devices that can translate foreign languages as fast as you can talk; materials 10 times stronger than steel at a fraction of the weight; and—this is unbelievable to me—molecular computers the size of a tear drop with the power of today's fastest supercomputers." By the end of 2001, *Science* magazine proclaimed molecular electronics as the breakthrough of the year (Figure 1a),[6] adding more fuel to the increasingly pervasive belief that molecular computing had arrived.

While undoubtedly the vast majority of the pioneering work in the early days of the NNI was scientifically sound and important, the peak of inflated expectations created a level of excitement bordering on hysteria where unsubstantiated and even fabricated results crept into the most prestigious scientific journals. The infamous data falsification case of Jan Hendirk Schön at Bell Laboratories[7] can perhaps be identified as the nadir in the subsequent trough of disillusionment. However, it is worth noting that the Schön scandal was promptly identified, investigated, and resolved by the nanoscience and nanotechnology community, thus allowing the field to progress on the slope of enlightenment for the remainder of the decade. For example, the optimistic vision of imminent single-molecule and single-nanotube circuits (Figure 1a) has been replaced with pragmatic realizations of thin film semiconducting carbon nanotube transistors (Figure 1b)[8] and digital circuits (Figure 1c).[9]

In 2011, it can be debated if nanoscience and nanotechnology remain on the slope of enlightenment or have entered the plateau of productivity; almost certainly that assessment depends on the specific subfield that is being discussed. For instance, the 32-nm silicon transistor technology that underlies the $100 billion microelectronics industry is evidently a proven and productive nanotechnology, whereas the potential of nanobiosystems for diagnostics, imaging, and therapeutics has likely not yet been fully realized. In either case, the Nano2 study has concluded that the field of nanoscience and nanotechnology has matured from the early days of the NNI and now underlies technological advances that touch nearly all aspects of society.

10.1021/nn103470j

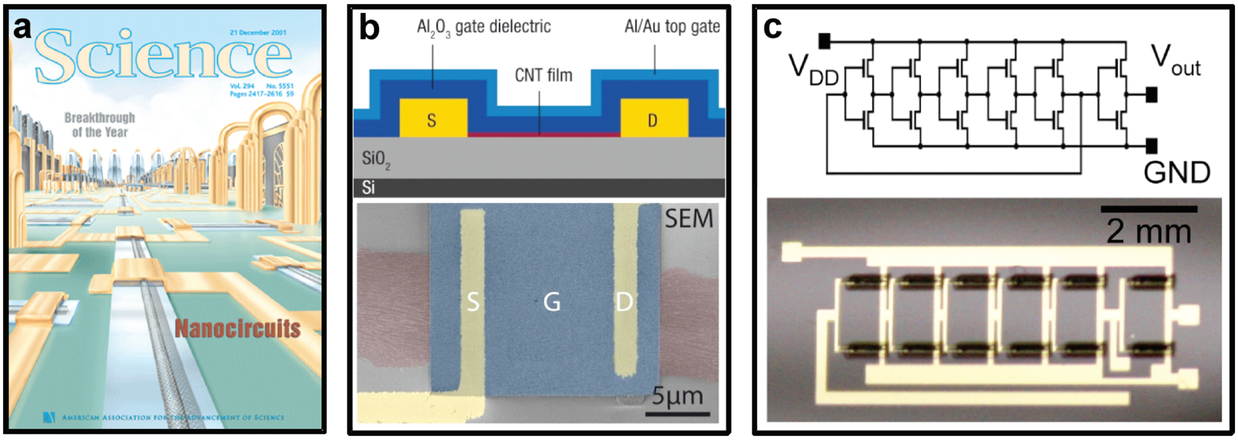

Figure 1. (a) The hype surrounding nanoscience and nanotechnology reached a feverish pitch in 2001 as single-molecule and single-nanotube circuits graced the cover of the "breakthrough of the year" issue of *Science* magazine.[6] Reprinted with permission from ref 6. Copyright 2001 American Association for the Advancement of Science. (b,c) In the posthype era, many of the visionary notions cultivated in the early days of the NNI are now being realized in practical contexts: (b) thin film semiconducting carbon nanotube transistors from IBM;[8] (c) printed, flexible, low-voltage digital electronic circuits from aqueous carbon nanotube inks.[9] Reprinted from refs 8 and 9. Copyright 2008 and 2009 American Chemical Society.

Looking to the future, the Nano2 study makes the following overarching recommendations for the next decade: (1) while many of the early discoveries are well-poised to become manufacturable technologies, the discovery phase is far from over, thus underlining the importance of continued fundamental research in this field; and (2) the field needs to communicate the structure, opportunities, and challenges for nanoscience and nanotechnology at all levels of education and public outreach. Likewise, as nanotechnology leads to increasingly diverse materials and manufacturing, environmental health and safety and regulation become important issues, as discussed in a Nano Focus and a Perspective, respectively, in this issue.[10,11] With its diverse content, including comprehensive research articles, topical reviews, perspectives addressing unanswered questions, conversations with leading experts, and nano focus articles on meetings, policy, and education, *ACS Nano* is well-positioned to help achieve these goals and thus shape the development of nanoscience and nanotechnology in the posthype era.

Mark Hersam
Associate Editor

REFERENCES AND NOTES

1. Bonnell, D. The Next Decade of Nanoscience and Nanotechnology. *ACS Nano* **2010**, *4*, 6293–6294.
2. Roco, M. C., Mirkin, C. A., Hersam, M. C., Eds. *Nanotechnology Research Directions for Societal Needs in 2020*; Springer: New York, 2011, in press. Also available at http://ww.wtec.org/nano2.
3. Jarvenppa, H.; Makinen, S. J. Empirically Detecting the Hype Cycle with the Life Cycle Indicators: An Exploratory Analysis of Three Technologies. *Intl. Conf. Ind. Eng. Eng. Manage.* **2008**, *1*, 12–16.
4. Roco, M. C., Williams, R. S., Alivisatos, P., Eds. *Nanotechnology Research Directions: IWGN Workshop Report. Vision for Nanotechnology R&D in the Next Decade*; National Science and Technology Council: Washington, DC, 1999.
5. Siegel, R., Hu, E., Roco, M. C., Eds. *Nanostructure Science and Technology*; National Science and Technology Council: Washington, DC, 1999.
6. Service, R. F. Breakthrough of the Year: Molecules Get Wired. *Science* **2001**, *294*, 2442–2443.
7. Service, R. F. Bell Labs Fires Star Physicist Found Guilty of Forging Data. *Science* **2002**, *298*, 30–31.
8. Engel, M.; Small, J. P.; Steiner, M.; Freitag, M.; Green, A. A.; Hersam, M. C.; Avouris, P. Thin Film Nanotube Transistors Based on Self-Assembled, Aligned, Semiconducing Carbon Nanotube Arrays. *ACS Nano* **2008**, *2*, 2445–2452.
9. Ha, M.; Xia, Yu; Green, A. A.; Zhang, W.; Renn, M. J.; Kim, C. H.; Hersam, M. C.; Frisbie, C. D. Printed, Sub-3V Digital Circuits on Plastic from Aqueous Carbon Nanotube Inks. *ACS Nano* **2010**, *4*, 4388–4395.
10. Thomas, R.; George, S.; Horst, A. M.; Ji, Z.; Miller, R. J.; Peralta-Videa, J. R.; Xia, T.; Pokhrel, S.; Mädler, L.; Gardea-Torresdey, J. L.; *et al*. Nanomaterials in the Environment: From Materials to High-Throughput Screening to Organisms. *ACS Nano* **2011**, *5*, 13–20.
11. Malloy, T. F. Nanotechnology Regulation: A Study in Claims Making. *ACS Nano* **2011**, *5*, 5–12.