Nanotechnology and manufacturability

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Between a promising initial result in a laboratory and the commercial availability of a product there are many hoops to jump through, and indeed there is a severe attrition rate so that few results actually make it to products. In this article, I want to focus on the technical aspects of achieving a manufacturable prototype, but it must be remembered that commercial success is based on customers actually wanting to buy the product in the market place at the price on offer. I am particularly concerned about the issue of manufacturability precisely because is not the concern of the authors of the vast majority of papers that appear under the title of nanotechnology, and the subset in nanoelectronics. Indeed I think that the problem is so serious that there will be a well-deserved backlash against the whole of nanoscience if it is not rectified soon.

Let me explain. It is one thing—science—to make one-off nanoscale artefacts in the laboratory and to study their interesting properties; it is quite another—technology—that allows a product to be manufactured. Low-cost, high volume manufacture requires more than one-off fabrication. Indeed it needs all three of:

- a superior prespecified performance achieved with reproducibility, uniformity and reliability;
- a high yield to acceptable tolerance;
- a simulator for both reverse engineering during development and right-first-time design.

It is interesting to see via a computer search just how few papers in the nanotechnology literature include the words "yield" or "uniformity" or "reproducibility". When I ask seminar speakers to comment on their yield or reproducibility, they tend to look blankly at me!

In mainstream microelectronics, many trillions of dollars have been invested so that modern memory and microprocessor chips can be manufactured, and the key feature sizes of transistors are at the scale of a few tens of nanometres across the surface and a few layers of atoms below the surface of the semiconductor.[1] This is the clearest existence theorem for nanometre-scale products. It is pure cant for researchers to posit that what they are doing might

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[1] See the International Technology Roadmap for Semiconductors on www.itrs.net

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be the basis of a post-silicon CMOS technology, in the absence of positive results at the starting point of any *technology*—which is the ability to reproduce results consistently within a tight tolerance and to be able to modify the results to order.

There are limits on the performance of electronic and optical devices because of the values of fundamental constants such as the speed of light and the charge and mass of an electron. There are limits from the basic materials properties of semiconductors (in particular the saturated drift velocity of the carriers and the dielectric breakdown electric field), the so-called Johnson criteria.[2] In contrast, there are no simply stated limits on what can be got out of devices by virtue of how they are made, and this has concerned me. Nearly three years ago, I proved a theorem that shows that trying to make arrays consisting of 3 nm diameter features on a 6 nm pitch is not possible—they are intrinsically impossible to manufacture using the top–down techniques of epitaxy, lithography and etching that are the underlying basis of microelectronic fabrication. The problem is the uncontrollable variation in feature size from one feature to the next in the array. Each layer of each pillar contains 80 atoms, and is formed by adding or removing atoms one at a time by deposition or etching. Since $\sqrt{80} = 9$, the coefficient of variation (one standard deviation, σ, divided by the mean) of the area of these pillars is 12%, whereas today's silicon chip technology works with $\sigma < 2\%$ in terms of transistor performance. I suspect that the interface between manufacturability and unmanufacturability is actually closer to 7 nm rather than the 3 nm discussed above. Furthermore, even if one could make one pillar an atom at a time by a heroic effort (à la Feynman[3]), one could never address, store or read out any information with such small features.

The fate of the journal submission of the paper containing this theorem reveals a very unattractive side of much of modern science, and nanotechnology in particular. Over a period of 30 months, the paper was turned down ten times by each of seven journals, and not because it was wrong, trivial or derivative, but rather because it did not, by virtue of its profoundly negative finding, fit the journal's upbeat tone. "We only publish hot new physics" and "we do not want to admit defeat while so much fun and progress is being made in nanotechnology" were two responses, and a third suggested I go to the press and other media to complain! Note that it was journal-based editors, not my peers, who made these comments. Twenty or more years ago, profoundly negative papers did get published—they challenged the emerging orthodoxies in the subject and led to a flurry of work to counter the criticism or to concede its correctness. The subject would progress or change direction accordingly, to the good of both science and technology. When commercial journals and those owned by professional bodies are more concerned about their own image in the marketplace of journals than in the intrinsic health of their subject, I am concerned. Apparently no journal these days wants to be associated with a paper that kills off a branch of their subject, or raises questions about the continued scale of funding! It is bad for science if new orthodoxies are being established prematurely and without the cut and thrust of deep internal criticism—I am sure that this is part of the problem in climate science. On the 11th attempt at submission all three peer reviewers made the point that this

2 E.O. Johnson, Physical limitations on the frequency and power parameters of transistors. *RCA Review* **26** (1965) 163–177.

3 R.P. Feynman, "*Plenty of Room at the Bottom*", December 1959 (retrievable from http://www.its.caltech.edu/~feynman/plenty.html).

paper needed publication on its merits and for the sake of its important and controversial contents. One made further suggestions to broaden the scope of possible implications beyond electronics and optoelectronics into all forms of sensing and nanomechanics. Another suggested that the journal should publicize the paper, and the invitation to write this piece is one outcome. The title of the published paper,[4] "Intrinsic top-down unmanufacturability", was repeated on over 1400 different web pages within a month of publication. My paper included a reference to http://www.eng.cam.ac.uk/~mjk1/102 CITATIONS.htm, which in turn includes quotations from 102 papers, representative of thousands in nanoscience rather than nanotechnology, which make pious acknowledgment that manufacturability remains an untackled challenge. I think that the same theorem will apply to bottom–up, self-assembly type of fabrication as well, but I have not proved it to my satisfaction. A template of small dents in the surface of a wafer may encourage small molecules to sit in arrays without line defects, but whether the error rate can be reduced to a few in a million is not proven, but could be experimentally.[5] The problem of addressing and reading from the elements of this array is still deeply problematic. When silicon miniaturization ceases, it is not material issues but variability and uncontrolled leakage at play and this latter will plague any molecular alternatives.

Why do I think there might be a backlash against nanotechnology? At a time of global financial shortages, science and technology are not immune from taking some share of the pain. There were outcries in the UK when a prominent engineer suggested recently that answers to the fundamental questions of the cosmos could wait a few years while the country restored its finances! When it comes to sharing out the pain in the wider and more practically applicable sciences we have a different issue to face. The public funds science for two reasons: (i) it is the character of civilized mankind to be curious about the nature; and (ii) much of modern civilization is based on the fruits of previous research has been turned into useful products that enhance the capabilities of individuals and societies. The scale of funding of the latter is much greater than the former, and it accounts for most funding given to nanotechnology. If an independent review, anywhere in the world, were to conclude that most of the research in progress is curiosity-driven fun and is actually blind to the practical demands of real product development, there would be public and political outrage and rapid budget reorganization.

I have just one practical suggestion that would provide a real defence again such an outcome. Every paper submitted to a nanotechnology journal should actually describe *technology* experiments (on initial yield, uniformity, tunability etc.) as a clear and unambiguous precondition for consideration for publication: if this material is absent the paper should be sent back to the author. In this way the technological, as opposed to the scientific, aspects would get appropriate attention. The results would be more effective through winnowing out failing technologies at an earlier stage. Public faith in their investment in nanotechnology would be more honoured by the practitioners. This would be a simple quality assurance mechanism, it would protect the subject and accelerate its advance, and it would put considerations of technology, engineerability and manufacturability on centre stage. The technology in nanotechnology would henceforth mean what it says.

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4 M.J. Kelly, Intrinsic top-down unmanufacturability. *Nanotechnology* **22** (2011) 234303.
5 J.Y. Cheng, C.A. Ross, E.L. Thomas, H.I. Smith and G.J. Vancso, Fabrication of nanostructures with long-range order using block copolymer lithography. *Applied Physics Letters* **81** (2002) 3657–3659.