On the Integration of Micro and Nano Scale Engineering
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ABSTRACT

This paper attempts to present a balanced perspective of the two emerging technologies of microsystems technology (MST) and nanotechnology (NT). An outline on the difference in scientific bases from which these two technologies are evolved is presented. In reality, however, it is necessary to integrate these two technologies in producing viable industrial products as illustrated in the paper.

1. Miniaturization – the leading technology of the Century

There appears a general consensus among members of the science and engineering communities that “miniaturization”, in particular, the nanotechnology will dominate the technological development in the 21st Century. Indeed, there have been numerous forums, symposia and conferences dedicated to this popular topic in recent years sponsored by governments, research and academic institutions, and prominent professional societies around the world. New books and conference proceedings on nanotechnology and NEMS (an abbreviation of NanoElectroMechanical Systems) have been added to the already-long publication lists at all times in the last two years.

The revenue generated by nanotechnology has been truly impressive. Sources indicated that the annual revenue generated by this technology amounts to $50 million in Year 2001. If one includes products involving parts produced by nanotechnology, the annual revenue had jumped to a staggering $26.5 billion in Year 2003. The US National Science Foundation predicted that the annual revenue generated by nanotechnology would reach $1 trillion in Year 2015. Such lucrative revenue forecast has prompted governments of leading industrialized nations in the world investing heavily in the R&D of nanotechnology.

2. The Origin of Miniaturization

The concept and engineering practices in miniaturizing industrial products is not new. One well-known example is the miniaturization of digital computers from the size of three-roomful of vacuum tubes and electrical circuits with relays and switches in the first digital computer by the name of ENIAC built in 1946 to the current palm-top
computer with an approximate $10^6$ times in size reduction but having $10^8$ times more computational power [1]. The evolution of cellular telephones in the last decade provides another example of dramatic miniaturization of industrial products. In such case, the reduction of physical size of the telephone sets may not be as spectacular as that of digital computers, but the functions of these sets have been substantially extended from simple transceiving of voice messages to what they can do today in additional transceiving of color pictures, video images as well as functioning as personal computers for user’s accessing the Internet. It was the miniaturization of various functional components that are packaged in these smaller telephone sets that has made multi-purpose and multifunctional cellular phones possible. The unequivocal trend in strong market demands for intelligent multi-functional devices has made miniaturization of device components ever more urgent by the industry, and the technologies that enable industry miniaturizing its products have thus become the prime driving force to the nation’s economy in the new Century.

The two prevailing technologies that enable drastic miniaturization of industrial products in the last decade are microsystems technology (MST) and nanotechnology (NT). The MST, which is referred to as the “top-down” approach in miniaturization, evolves from the invention of transistors by three Nobel Laureates, W. Schockley, J. Bardeen and W. H. Brattain in 1947 [1]. The current hyper active R&D activities in nanotechnology are inspired by a famous speech delivered by another Nobel Laureate, Richard Feynman in 1959 [2]. Nanotechnology is regarded as a “bottom-up” approach in miniaturization. A generally accepted definition of these two approaches is illustrated in Figure 1.

![Figure 1 The Two Approaches in Miniaturization](image)

3. The fundamental Differences between MST and NT

Table 1 outlines major differences between MST and NT. We will notice that solid physics is the scientific base on which the MST is developed. The NT, on the other hand, is built on quantum physics and quantum mechanics. One may argue that solid physics, after all, is a subset of quantum physics and the two emerging technologies should be perceived as evolving from the same basic science of quantum physics. The
counter argument to this, however, is that the physics of the MST is primarily on the conductivity of electricity and the physical-chemical reactions of materials but not on the physical-chemical bonds and mobility of atoms as emphasized in the NT. Some of the promising fabrication techniques for producing nano scale products also involve molecular biochemical syntheses, which is radically different from those used in MST.

In spite of the strong enthusiasm expressed by scientists and engineers and their high expectations on the potential benefits of NT, and the colossal amount of monies that have been invested in the R&D by governments of industrialized nations, its extreme diverse nature has made nanotechnology remaining at the stage of “technological development” in laboratory environments as indicated in Table 1. The availability of nano scale devices and their commercialization appear to be many years down the road.

Table 1 Comparison of Micro and Nano Scale Technologies

<table>
<thead>
<tr>
<th>Microsystems Technology (MST)</th>
<th>Nanotechnology (NT)</th>
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<tbody>
<tr>
<td>Top-down approach</td>
<td>Bottom-up approach</td>
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<tr>
<td>Miniaturization with micro meter and sub-micro meter tolerances</td>
<td>Miniaturization with atomic accuracy</td>
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<tr>
<td>Builds on solid state physics</td>
<td>Builds on quantum physics</td>
</tr>
<tr>
<td>Evolves from IC fabrication technology</td>
<td>Evolves from quantum physics and molecular biochemistry</td>
</tr>
<tr>
<td>Established techniques for producing electromechanical functions</td>
<td>Not yet developed</td>
</tr>
<tr>
<td>Well established fabrication techniques</td>
<td>Fabrication techniques are in research stage. Some are radically different from those used in MST</td>
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<tr>
<td>Proven devices and engineering systems in marketplace</td>
<td>A handful simple geometry nano scale products available</td>
</tr>
<tr>
<td>Success in commercialization of a few products</td>
<td>A long way to go to commercialization</td>
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</tbody>
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4. Major Accomplishments of MST and NT

Twenty years of active R&D in MST have lead to significant success in commercialization of micro scaled products as shown in Figure 2. Most of these success cases are in biomedical and automobile industries. Detail descriptions of these products and their applications are available in references [1, 3]. Annual revenue generated by MST in the world will be between $43 billion to $132 billion by Year 2005. The higher end of this projected revenue is based on the broader definitions used for the MST products. One example is the inclusion of read/write heads of data storage systems and ink-jet printer heads as MST products. Full capitalization of MST, however, has yet to
be realized due to lack of standardization in design, manufacture and materials, and above all, the awkward packaging techniques [1, 4].

Significant R&D in nanotechnology did not happen until about a decade ago despite the fact that the first man-made nano scaled structure called “Buckyball” was produced by a Nobel Laureate, Richard Smalley in 1985. The Buckyball was made of 60 carbon atoms in the shape of a soccer ball with 0.7 nm in diameter. Many attribute the active R&D in nanotechnology to the work of a pioneer scientist by the name of Eric Drexler [5].

![Figure 2 Major Industrial Products with Microsystems Technology](image)

Scientists and engineers have anticipated enormous benefits that the NT will bring to human civilization. Major impacts by NT are expected to be on the following eight industrial sectors: (1) Electronics, computing and data storage. (2) Materials and manufacturing. (3) Health and biomedicine. (4) Energy and environment. (5) Transportation. (6) Agriculture and food processing. (7) Aerospace. (8) National security, search and rescue. Prevalent nano products have been limited to the following three basic types:

1. **Nano dots** (or particles) that are used as smart coating materials and paints for automobiles and structures. These materials are typically tough and enduring. Their properties can change for the better in responding to the change of environmental conditions. Nano particles have also been used in noble cosmetic products.
2. Nano wires that are used in molecular electronics as gates and switches. Some nano wires are also used in nano scale sensors and smart composites.
3. Nano tubes for structure supports and nano scaled fluidics.
5. Fabrication Techniques for Micro and Nano Scale Products

Principal techniques involved in the fabrication of microsystems are described in reference [1]. Photolithography is used to establish micro patterns of microsystems on mostly silicon-based substrates. The complex 3-D geometry of microsystems may be produced by sequential deposition of thin films using such techniques as chemical vapor deposition (CVD) or physical vapor deposition (PVD), known as sputtering. The complex 3-D geometry can also be created by etching processes using chemical solvents in “wet” etching or plasmas in “dry” etching. Expitaxial growth is used to build up geometry of the same substrate materials. Other processes such as ion implantation and diffusion are often used in doping silicon substrates for p-n junctions and piezoresistors in microsystems. Oxidation of silicon provides necessary localized electrical or thermal insulations in the micro structures.

Fabrication of nano scale products such as wires, tubes or other structure components of complex geometry such as described in the foregoing section remains in an early stage of development. In general, it involves three major steps in the process as described below:

**Step 1: Isolation of atoms or molecules from the substrates.**

Early development involved the use of atomic force microscope (AFM) or scanning tunneling microscope (STM) to free atoms from the surface of substrate materials. Recent development uses high energy plasma etching with ion or electron beams.

**Step 2: Assembly of loose atoms or molecules.**

The newly freed atoms or molecules need to be assembled into the shapes of wires or tubes, or other desired geometry of the end product. Recently developed tools such as AFM-guided nanomachining system (AGN) may be used for this purpose. Considerable R&D effort is being made in molecular self-assembly techniques by biochemical or electromechanical means.

**Step 3: Re-bonding free atoms or molecules.**

Re-bonding of loosely assembled atoms and molecules can be achieved by vaporizing the assembled free atoms at high temperature in high vacuum, followed by carefully controlled condensation. Alternatively, one may use chemical synthesis involving combined diffusion and chemical reactions in CVD-like processes. Biochemical synthesis such as “natural molecular machine” for growing proteins, enzymes and antibodies are being developed for this purpose.
6. Integration of MST and NT

The bright prospects of miniaturization of industrial products by the two radically
different approaches as indicated in Figure 1 has prompted rapid emergence in
integrating the MST and NT in new engineering systems and industrial product
developments. The following two cases will illustrate how these two emerging
technologies can be integrated in developing viable industrial products.

Case 1: The emergence of nano transistors.

Figure 3 shows a roadmap for future generations of transistors to Year 2017 developed
by the Intel Corporation [6].

In Figure 3 shows that the MST has been and will be used to produce the transistors
with nodes as small as 32 nm up to Year 2009. Further reduction in sizes has been

![Figure 3 A Roadmap for Nano Scale Transistors](image)

...projected to Year 2017, but with less certainty on the fabrication techniques for
producing these miniature transistors. As matter of fact, many experts have cast doubts
whether the improved micro fabrication can be used to produce transistor with 32 nm
node size as set for Year 2009. Electrical leakage and heat dissipation will be the two
major stumbling blocks in further miniaturizing transistors with node size below 45 nm.
These two major technical problems could be solved by using the MST to provide for
instance molecular tunnels or micro heat pipes for dissipating excessive heat. The
electrical leakage may be minimized by using thin films made of high dielectric, or high
k-materials using micro fabrication techniques.

Case 2: The tera-bits data storage systems – The Millepede project [7]

IBM initiated this project little over a decade ago. The principle for achieving ultra high
density data storage in this development is to produce nano scale dents of the size of 40
nm on the surface of a thin polymeric coating over a silicon substrate using atomic force microscopes (AFM) with heated tips. The thermomechanical forces produced by the AFM can produce dents with desired depth and thus distinct data bits on the polymer coating. Retrieval of data can be accomplished by a reversed effect on the AFM without heated tips. Erasing of data is possible by annealing the polyamide near the glass transition temperature. With AFM tips with array size of 32 x 32, a storage density greater than 400 Gbits/sq.in. was achieved as shown in Figure 4. The AFM with sharp heated tips produced by the MST has shown to be able to produce nano scale data bits in this promising ultra high density data storage system.

7. **System Integration with MST and NT**

One of the major difficult tasks in MST is the integration of the micro scale device components with the required microelectronics for signal or function processing. The same difficulty will sure be encountered by engineers in miniaturization of industrial products with system-on-chip (SoC), in which components produced by MST and NT is expected to be integrated into a single system. Packaging of these components will be a formidable challenge to engineers in resolving the issues relating to interfacings in geometry and environments, tolerance settings and the bonding and sealing. The integrated micro and nano scale components need to be further integrated with microelectronics as in the case of microsystems. Additionally, it will be a horrendous challenge in fabricating micro scale components using the micro fabrication techniques described in Section 5 and have the same substrate to grow nano scale components using biochemical synthesis process. Testing of SoC for reliability will be another major problem to engineers as there has been virtually no standard and tools ever developed for this critical task in any product development and marketing.

Figure 4 Nano Scale Data Bits on Polymeric Coating Using Integrated MST and NT
8. Summary and Conclusion

New “discoveries” of nano products and new applications of nanotechnology have been reported by the scientific community and start-up companies almost on daily bases. This over-zealous advocating of nanotechnology by many interest groups has stirred up sufficient public perception and high expectations that have resulted in enormous governments’ funding to the R&D of this technology over other worthwhile technological developments. This preferential funding practice has prompted many scientists and engineers worrying on possible negative consequences. One such consequence, as perceived by many, is that the real outcome of many currently funded R&D projects in nanotechnology will not live up to the unrealistically high expectations by the general public. This concern is not without logical basis as nanotechnology, as it stands now, has less than clear focus and its definition remains unsettled. One columnist viewed the nanotechnology to be at a crossroads somewhere between ‘hypothesis’ and ‘hype’ [8]. For example, the two icons in nanotechnology, Eric Drexler and Richard Smalley, each has his own definition for the nanotechnology. Drexler advocates “molecular self-assembly” to be the true nanotechnology. Smalley, on the other hand, defines his group’s activities in nano scale materials development to be the real nanotechnology. There are yet other views on what nanotechnology really is as expressed by many prominent scientists. Furthermore, many researchers, including the author, believe that the current government funding practices appear lack of broad perspective in embracing the engineering aspects of the NT, which includes the design and manufacture of the integrated MST, NT and the microelectronics as described in the foregoing section. Strong emphasis on the assembly, packaging and testing of SoC with integrated micro-nano scale components should be strongly encouraged and supported by the funding agencies. The current funding practice with over emphases on the science and components fabrication aspects of nanotechnology over the same for the MST is not only unwise but it will also hinder the chance of ultimate commercialization of NT. The two cases presented in Section 6 of this paper have demonstrated the value and the need for integrating micro and nano scale technologies in developing viable advanced industrial products. Typically, MST is used to fabricate nano scale components and the NT can prompt further improvements of MST products. A proper strategy in nano-micro-macro hierarchy is considered to be vital in future generation product development. Substantial R&D funding from governments and industry on the integration of NT and MST and microelectronics will provide best assurance on the fast return of the colossal investments that has already been made in the R&D of nanotechnology by many governments and industries around the world.

References


