Fundamental Issues in the Manufacturing of Nanoelectromechanical (NEMS) and Related Nanosystems

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***Abstract* – Nanostructures in dimension below about 10 nm show interesting properties because of the effect of low-dimension physics. However, to utilize these properties in practice to commercialize NEMS and related nano-systems require an extremely precise manufacturing process. This paper briefly evaluates the fundamental issues involved in manufacturing the nano-scale systems.**

***Index Terms* – NEMS, manufacturing nanoelectronics.**

I. INTRODUCTION

A Nanoelectromechanical System (NEMS) may include electronic, optical, magnetic, mechanical, chemical, biological, energy sources, and sensing components. To qualify as a nano-scale system, at least one of these functional components should have a dimension in the range of 1 - 100 nm and a property arising due to the extremely small size should be used by the system [1]. However, significant advantages are seen only at dimensions below about 10 nm, where quantum confinement effects are observed [2]. In the last two decades the MEMS technology has evolved from device manufacturing with right yield and functionality to system integration of devices such as oscillators, tunable filters, and auto focusing devices [3]. Extending the MEMS systems to NEMS [4, 5] systems provide opportunities in new functional capabilities of the system as well as overall cost reductions. However, there are key fundamental manufacturing challenges that must be solved before practical realization of NEMS systems can be realized [6]. The objective of this paper is to address key NEMS and related nano-systems manufacturing issues.

II. ADVANTAGES OF NEMS OVER MEMS

NEMS is fundamentally a scaled down version of MEMS with many advantages and applications. Due to the nano-dimensional feature sizes of NEMS, they have fundamental resonant frequencies that exceed 1GHz, better Q factors, and the ability to measure even mass with a resolution of about 10^{-21} grams [4, 7, 8]. NEMS have also been used to detect viruses captured from liquids [9]. Due to inherent advantages of NEMS, it is possible to develop high-resolution sensors, integrated low-power computational systems, and mechanical resonators etc. Proof-of-concept devices have already been shown to work in research labs.

However no manufacturing technique exists that can be used for manufacturing of NEMS and related nanosystems.

III. FUNDAMENTAL PROPERTIES OF MATERIALS AT NANOSCALE

Properties of materials are significantly different at nano-dimensions in comparison to those in the bulk; a general trend is shown in Fig. 1. For example, the melting point of gold changes by hundreds of degree Celsius as the particle size goes below 100 nm [10]. Sometimes, but not always, these different and new properties can be used for our advantages. For instance, a near defect-free material can be made when its dimension is below a critical dimension [11]. If these properties can be realized in practical devices, their applications will be immense.

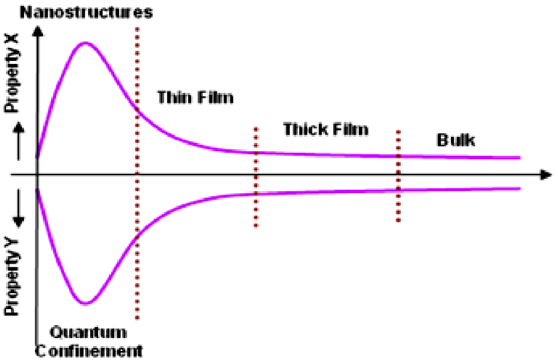

Fig.1. Properties of materials as a function of size.

IV. KEY FUNDAMENTAL ISSUES

To be able to manufacture nanoscale devices two fundamental considerations arise - nanostructure homogeneity and process variability [6]. Without considering these core issues, a proper manufacturing technique cannot be designed for a nanoscale device.

A. *Nanostructure Homogeneity*

The material used to make the nanostructure must be homogeneous in all directions, which implies that defects must be below an extremely small threshold. In addition, performance, reliability, and yield will be highest when the degree of homogeneity is high. This also involves reducing the variation in global and local thermal and residual stresses in the material [12,13].

B. *Process Variability*

Process variability is unavoidable during manufacturing and it will result in unequal nano-dimensions in the device. The important factor here is that the amount of variability should be kept under control. ITRS data shows that, to achieve a 22 nm half pitch, the line width roughness of the resist material should be less than 1.4 nm and the process should be able to align the device with an error less than 5.3 nm, all with a statistical variability of three [14]. This is a non-trivial problem when manufacturing nano-dimensions as the dimension being manufactured is itself only less than 10 nanometers and the required tolerances for each processing step could be less than 1 nm. In Table I we have listed the lithography control that either has been achieved for a particular dimension or is expected in future generation of lithography generated critical dimensions.

Thus, the control of dimension size is extremely important in manufacturing NEMS based systems. In Fig. 2, Distribution A shows the allowed variation in dimension sizes for exploiting the special properties that can be obtained with NEMS based devices; however, during manufacturing, due to a lack of absolute control on the dimension, the resulting distribution will resemble the Distribution B shown in Fig. 2. Reduced values of full width at half maximum (FWHM) will provide better performance, reliability and yield of NEMS.

TABLE 1: CRITICAL DIMENSION CONTROL

Critical Dimension (nm)	**Lithography Control Obtained and Predicted (3 σ) (nm)**	**Self Assembly Control Obtained (nm)**
27	2.8	
20	2.1	
21		3 [15]
15	1.6	
10	1	
7	0.8	

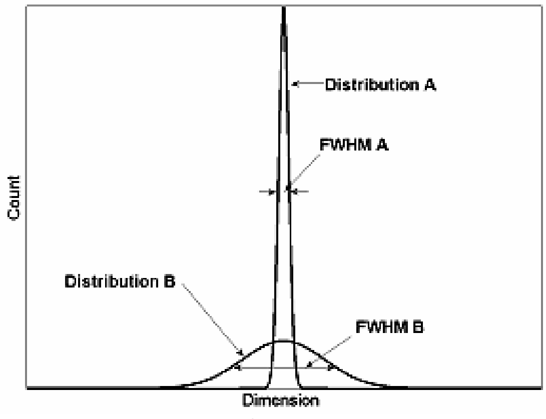

Fig. 2. Statistical distribution of dimensions (A = required and B = actually obtained).

V. CURRENT MANUFACTURING PROCESSES

To manufacture a NEMS in a commercially viable fashion, two technologies are currently under consideration. The first one is the standard top-down approach and the other is bottom-up approach. Both these prospective technologies are examined in this section.

A. Top-Down Approach

Lithography has been the standard technique for transferring patterns during IC manufacturing since its beginning. The minimum feature size, quantified as half-pitch has been steadily decreasing since the 1980s. Invention of better light sources and improved methods of exposure have driven this change. As of now, the half-pitch distance is 32nm and the light source used has a wavelength of 193 nm, which is about six times the half pitch distance [14]. Further decrease in the light source wavelength to 13.5 nm using an Extreme Ultra Violet source, has the possibility to decrease the half-pitch to the range of a few nanometers [14]. With lithography, patterns of half-pitch distance less than 10 nm have been created over a decade ago [16].

Apart from surface patterning abilities, manufacturing the NEMS will require profiling abilities along the vertical axis. The Deep Reactive Ion Etching process is currently able to make vertical profiles with aspect ratios greater than 50. Thus, the traditional, semiconductor industry, based manufacturing technology can make nano-dimensional structures for research purposes. However, issues relating to non-homogeneity and process control will determine if these devices can be successfully manufactured on a large scale without defect related problems. Recently, a defect on one of Intel's chip was discovered and analysts predict that this defect is going to cost Intel about $1 Billion [17]. Defects such as these will determine how successful a product will be.

B. Bottom-Up Approach

The bottom up approach involves devices using an atom-by-atom, approach and is called self assembly [18]. In our opinion the meanings of "Self Assembly" have been taken wrongly. True self assembly process involves programmed cell death or apoptosis [19]. The so called "self assembly" is actually selective chemistry. The atoms or molecules are forced by chemical, mechanical, or electrical means to assemble in a particular fashion. Researchers have often compared this method to the method employed in the development of an animal or a plant. This technology is relatively new and there is no commercially available system capable of performing self-assembly. To demonstrate the fundamental problems associated with "Self Assembly" we consider the growth of carbon nanotubes (CNTs). Scanning tunneling microscope (STM) is used to select CNT of desired length and diameter [15]. Even with the use of STM, CNTs of radius 21 ± 3 nm can be obtained. As shown in Table I, these results are not comparable to the lithography results. In a previous publication [20] we have investigated the basic nature of bio-driven systems and found that due to their fundamental nature of low growth rates as well as their high defect densities, it is highly unlikely that such systems can be used in semiconductor manufacturing.

VI. CONCLUSION

In this paper we have addressed the fundamental issues of nanostructure homogeneity and process variability for manufacturing NEMS and related nanosystems. The top down approach of lithography will continue to further scale down nano-dimension systems. However Bottom-up approach has fundamental limitations of high defect densities and low throughput.

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