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COMPLEXITY OF NANOMANUFACTURING

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ABSTRACT

This paper addresses how the complexity in micro- and nano-scale manufacturing can be understood and then reduced for real manufacturing of tiny products such as microchips and carbon nanotubes. The axiomatic interpretation of the monolithic idea for microchips shows that the information content could be drastically reduced by printing MOS transistors rather than assembling discrete transistors. It also shows that the information content well characterizes the real complexity of tiny product manufacturing. An effort to minimize the complexity of assembling nanostructures is described. A deterministic assembly process for carbon nanotubes has been developed as a part of this effort, which embeds a bundle of carbon nanotubes into micro-scale polymer blocks, which then can be transplanted, oriented and bonded readily. The block serves as a micro-scale carrier of nanostructures, facilitating their handling and assembly. More recently, we have developed a new transplanting process, which can assemble an individual carbon nanotube to a specific location. The new process produces high aspect ratio cylindrical blocks (nanocandles), each of which can carry a single-strand carbon nanotube. The buried carbon nanotube can later be exposed to function as a nano-tip for applications such as atomic-scale scanning, nano-pipetting, nano-thermal lithography, and tip enhanced Raman spectroscopy. The concept of transplanting assembly uncouples the functional requirements (FRs) of assembly from the functional requirements (FRs) of synthesis, and thereby could control each functional requirement optimally in assembling nanostructures such as carbon nanotubes. It also increases the overlap between the design range and the system range to minimize the information content for assembling nanostructures.

Keywords: complexity, nanomanufacturing, carbon nanotubes, deterministic assembly

1 INTRODUCTION

Many research groups have tried to build and assemble nanostructures bottom-up. The quantum dots, nanoparticles, nanotubes and nanowires are made at sub-nanometer scales. In order to benefit from the nanotechnology, those nanostructures need to be integrated to the micro/macro-scale systems, where the top-down and bottom-up manufacturing processes meet. This makes the design and manufacture of multi-scale systems very complex. The degree of complexity increases rapidly as the system scale order grows, which obviously is a very difficult task to achieve with the existing microfabrication technology.

Current nanotechnology has put a heavy focus on the nanomaterial synthesis, while very few manufacturing processes to integrate nanostructures to micro/macro structures are available at the present time. The most typical example is the assembly of carbon nanotubes. Carbon nanotubes (CNTs) elicited significant attention upon their discovery. There remain, however, few feasible methods for handling and assembling carbon nanotubes, thus limiting successful commercial applications to date. Current efforts for guided growth or self-assembly of carbon nanotubes cannot yet integrate them into micro/macro structures at deterministic locations. Dispersion of CNT soot into a polymer matrix is one of a few manufacturing options at the present time. Towards this goal, the author has developed a method for deterministic CNT assembly by transplanting carbon nanotubes to specific locations where they could function as nano-scale components. The concept of *transplanting* assembly uncouples the function of assembly from the function of synthesis. It also reduces the complexity associated with the handling and assembly of individual carbon nanotubes.

The axiomatic interpretation is made in this paper to understand how the complexity in fabricating microchips was reduced by the monolithic idea and how the transplanting assembly would reduce the complexity of nanomanufacturing. Lessons from the microchip development indicate that the axiomatic approach can provide a good framework to define novel functionalities and to better understand and reduce complexity of the upcoming nanomanufacturing. The goal of this paper is to extend the

Axiomatic approach in setting the right research direction to better deal with the complexity of nanomanufacturing in the future.

2 AXIOMATIC INTERPRETATION OF THE MONOLITHIC ASSEMBLY OF MICROCHIPS

With the invention of solid state transistors at Bell Laboratory in 1947, electrical engineers of the 1950s saw the possibilities of developing far more advanced and multifunctional circuits. The much smaller, faster and lower power consuming transistors quickly replaced the vacuum tube technology. However, as the complexity of the circuits grew, serious problems started arising. Since it was before the integrated circuit technology, workers had to assemble circuits manually, soldering each component and connecting them with metal wires. Engineers soon realized that manually assembling the vast number of tiny components was a very complex job and very costly as the number of components grew. They also realized that the wires interconnecting them became too long and the electric signals couldn't travel fast enough through the circuit, thus making the system too slow to function effectively. It was almost impossible to build advanced circuits containing so many components with the manual discrete assembly technology. This problem was known as the *tyranny of numbers* [1].

In 1958, Jack Kilby at Texas Instruments found a solution to this problem. Kilby's idea was to make all the components and the chip out of the same block (monolith) of semiconductor material. By fabricating all the parts on the same substrate and connecting them with a metal layer on top of it, there was no more soldering needed for individual discrete components. The circuits could be made much smaller and the manufacturing process could be automated. This idea of monolithic assembly has enabled the cost of microprocessor/memory chip remain almost the same while the number of components on a chip has been increased exponentially for the past 40 years. Jack Kilby received the Nobel Prize in Physics in the year 2000 for his idea of monolithic assembly of integrated circuits. Robert Noyce came up with his own idea for the integrated circuit half a year later than Jack Kilby. Noyce's circuit solved several practical problems that Kilby's circuit had, mainly the problem of interconnecting all the components on the chip. This was done by adding the metal layer and then removing partially so that the interconnection of the components could be formed. This made the integrated circuit more suitable for mass production. Robert Noyce became the co-founder of Intel which is still the largest manufacturers of integrated circuits in the world [2].

Moore's Law is a clear summary of the enormous impact this monolithic idea has made on the microelectronics technology and information processing [3]. Moore's Law has been the benchmark for the rate of growth in microprocessor technology, as the semiconductor industry must adhere to this rate if it is to remain competitive. Moore's Law describes that the number of transistors on a chip has been doubling every 18 months for the past 3 decades. In terms of complexity, the complexity of a chip has been doubled every 18 months at the same cost. The semiconductor manufacturing technology, in other words, has been enhanced to handle 20,000 times more complexity during the last 3 decades. It is the objective of this research examining the microchip manufacturing technology in terms of the complexity and finding out the potential enabling technology for the manufacturing of nanodevices in the future.

A relative measure of complexity has been introduced by Suh [4, 5], which has been built on the concept and framework of Axiomatic approach of design. In his complexity theory, complexity was defined as a measure of uncertainty in satisfying the functional requirements (FRs) within the specified accuracy. The Axiomatic approach to complexity can characterize the nature of complexity much better than the previous efforts by examining the uncertainty associated with the functions of a system rather than its physical entities.

Consider a microchip design which satisfies the Independence Axiom so that design parameters (DPs) are chosen to meet the FRs with either a diagonal or triangular design matrix. Real complexity is defined as a measure of uncertainty when the system range is not identical to the design range, which results the probability of achieving the FRs is less than 1.0. Thus real complexity can be related to the information content as

$$I = -\log_2 P$$

where P is the probability of satisfying the FR, which is defined as the ratio of the common range to the system range.

$$p = \frac{system\_range \cap design\_range}{systems\_range}$$

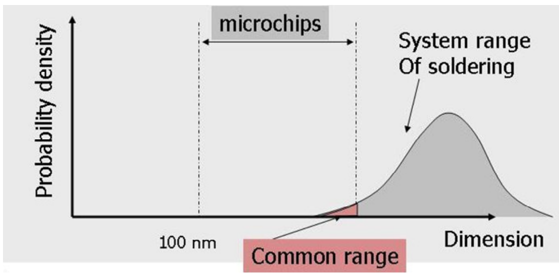


Figure 1 System range of the manual assembly of discrete parts has very little overlap with the design range of assembling microchips.

Figure 1 shows that the real complexity of manufacturing microchips would be very high since the system range of the manual soldering of discrete transistors would have very little common range to satisfy the FRs of the circuits containing many transistors. Since the physical size of the transistors became much smaller than bulky vacuum tubes, the manual assembly of discrete transistors would become even harder than assembling vacuum tubes. As the number of parts increases, this complexity will add up very quickly. Consider a Pentium chip which has 3.3 million transistors integrated into one chip. If a Pentium chip would be assembled by soldering discrete transistors which would cost 1 cent per soldering point, the cost of manufacturing would easily reach $300,000 to assemble one chip. It is very expensive and will not certainly justify any possible business even without considering the length problem of the very long interconnection. The actual manufacturing cost of one Pentium chip die when it was first introduced in 1994 was $417 with a very poor 9% yield. This would not be achieved without the invention of the monolithic idea and subsequent semiconductor manufacturing processes. Figure 2 illustrates that the monolithic idea provided appropriate assembling processes so that the system range could have much bigger common range to satisfy the FRs for fabricating microchips.

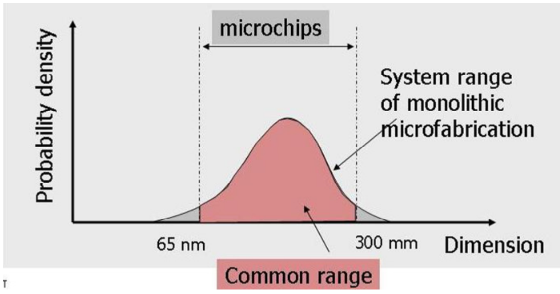


Figure 2 The monolithic idea could make the system range of microprocessor manufacturing overlap well with the design range with the 12 inch wafer processing capability and the minimum feature size of 65 nm.

Now we see the limit of the semiconductor manufacturing technology based on the monolithic idea. The system range has much less overlap now with the design range when the minimum feature size shrinks to smaller than 65 nm. In other words, the complexity of the current optical lithography based microfabrication goes up sharply with the minimum feature size gets smaller and smaller. Many have forecasted that the limit of the optical lithographic technology would pose the brick wall to the growth in microprocessor technology, while the limit of the optical patterning technology has been gradually improved to near 65 nm features. Extremely short wavelength lithographic technologies, such as EUV and X-ray, have been developed to pattern features smaller than this limit. However, the cost of using them to the mass production is expected to be very high, which can be interpreted at the increase of real complexity as shown in Figure 3. The real roadblock to manufacture chips with nanofeatures is not the absence of nanopatterning technology but the enormous complexity (cost) of them. In this regard, the focus of the nanomanufacturing research should be aligned on finding a proper manufacturing technology with acceptable amount of complexity, like the monolithic idea solved the *tyranny of numbers* 50 years ago. Many nanostructures have been developed in recent years and found to be very useful. It is, however, virtually impossible to assemble them to a multiscale system with the current monolithic assembly technology for microchips. This problem may be named as the *tyranny of scales*, since it is almost the same challenge we faced when the solid state transistor was invented but no proper method to assemble them was available. The key quest in nanomanufacturing, in this regard, is finding out a proper method to design and manufacture nanostructures which can be assembled to deterministic locations in a multi-scale system while preserving the FRs of the nanostructure during the assembly as shown in Figure 4.

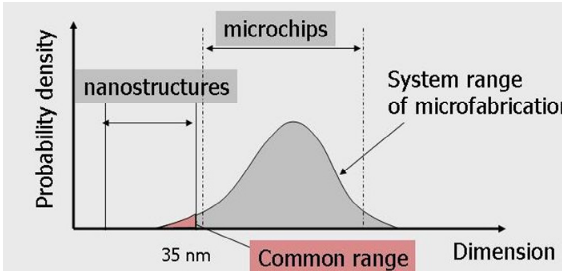


Figure 3 The system range of microfabrication processes has very little overlap with the design range of the assembly of nanostructures.

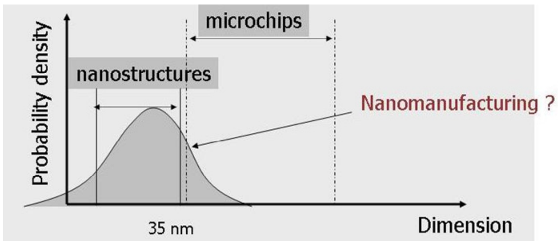


Figure 4 What is the right nanomanufacturing process to have a big overlap with the design range of assembling nanostructures?

3 TRANSPLANTING IDEA

Carbon nanotubes (CNTs) elicited significant attention upon the discovery of their existence and exceptional physical and chemical properties of them have been reported for many potential applications. There remain, however, few feasible methods for handling and assembling carbon nanotubes deterministically, thus limiting successful commercial applications to date [6-12]. Random dispersion of carbon nanotube soot into a polymer matrix is one of the few manufacturing options at the present time. Parallel and deterministic assembly is essential to manufacture functional nanostructures with practical values such as molecular scale transistors, ultra high speed chip interconnections, nanosensor arrays and nanoscanning probes. Current efforts of self-assembly of carbon nanotubes, however, cannot yet integrate them into micro/macro structures deterministically. Jin et al. [13] showed that one dimensional short nanowires were assembled into parallel arrays by a Langmuir-Blodgett method, which could align 1-D nanowires in a fluid flow without controlling individual wires.

The term "deterministic assembly" means the assembly with controls of location, orientation, length, rate, yield and range of order. In order to have a deterministic assembly of carbon nanotubes, Ye et al. [14] and Yenilmez et al. [15] have tried to grow carbon nanotubes at locations where their functions are needed. By seeding catalytic particles onto the Si tip of atomic force microscope (AFM) cantilevers on a Si wafer with the subsequent CVD process, long nanotubes grew extending out of the Si tips, which could be consoled to one good nanotube (if there is any). Since the yield of growth process cannot be perfect, a redundancy by seeding multiple catalytic particles is necessary.

A concept for deterministic carbon nanotube assembly has been developed by the author by decoupling growing from assembling carbon nanotubes [16, 17]. The key idea of the concept includes growing carbon nanotubes vertically at an optimal growth condition, preserving the vertical orientation by freezing the carbon nanotubes into a polymeric pellet, trimming them to have a specific length and transplanting them to the specific locations where they could function as nano scale components. Consider the case of growing healthy flowers in an ideal green house environment, growing one stem in one pot, and transplanting pots into arbitrary locations of the outside flower bed by relocating individual pot. This will make a well patterned flower bed with the highest probability of success while the existing seeding and growing method cannot assure the success of patterned assembly due to the poor yield of seeding and growing processes. The concept of transplanting assembly uncouples the function of assembly from the function of synthesis (or growth), and could thereby control each function optimally in assembling any nanostructure as well as carbon nanotubes.

The key challenges to implement this concept can be grouped into three categories: vertical growing, encapsulating, and transplanting. Carbon nanotubes are grown vertically in bunches on the patterned metal catalyst (Ti with 25nm thickness and Ni, 15nm) using plasma enhanced CVD machine built by the author. Among various carbon nanotubes growing methods such as arc discharge, pyrolysis, laser vaporization, thermal CVD, plasma enhanced CVD has received considerable attention because plasma enhanced CVD can grow vertically aligned carbon nanotubes at a relatively low temperature with a high yield. A DC plasma type reactor is built because the design is simple and the vertical growth mechanism of carbon nanotubes under DC bias voltage is well controllable. The DC plasma reactor consists of a pair of electrode in a grounded chamber with one electrode grounded and the other connected to a power supply. The negative DC bias voltage applied to the cathode dissociates the feedstock gas and generates many carbon-bearing radicals for carbon nanotube growth. Carbon nanotubes grow via the decomposition of the carbonaceous gas over a catalyst surface, diffusion of the carbon atoms through the catalyst, and subsequent accumulation of the carbon atoms. The carbon nanotube's electric dipole, accruing from the electric field exerted on the carbon nanotube, interacts with the electric field and experiences an alignment torque, developing stresses at the interface between the carbon nanotube and the catalyst particle. Since the diffusion flux depends on the stress gradient as well as the concentration gradient, stress induced fluctuations of diffusion rate can be a primary mechanism for the electric field induced vertical alignment of the nanotube.

A nanopellet is a polymeric pellet with a carbon nanotube (or nanotubes) embedded with its orientation preserved. Nanopellets are micro scale building blocks which can be easily handled by micro grippers or self assembled into a predefined pattern with a long range order. Therefore embedding carbon nanotubes into micro scale pellets will enable robust, repeatable, and large scale assembly of them. We have developed processes for the production of these pellets, which utilize a subtractive method whereby trenches are created in silicon wafer that then serve as molds for the nanopellets (Figure 5). Standard microelectromechanical systems (MEMS) fabrication processes and tools are utilized. The steps to create a nanopellet include the creation of trenches in which carbon nanotubes are grown via plasma enhanced CVD process. In order to freeze the orientation of vertically grown carbon nanotubes, the trenches are then filled with a spin coated epoxy polymer, encapsulating the carbon nanotubes. The surface of the filled epoxy is then planarized via chemical mechanical polishing (CMP) process to create pellets polished to the height of the Si trenches and to leave carbon nanotubes with uniform length. The epoxy pellets are released from the Si substrate using XeF_2 etching. The XeF_2 is a dry etchant which selectively undercuts only the silicon and releases epoxy pellets from the Si substrate. Similarly, the epoxy body material of the pellet can be selectively removed by O_2 plasma when it is necessary to expose embedded carbon nanotubes.

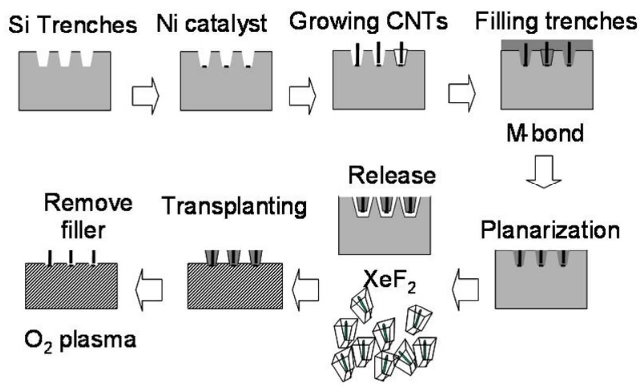
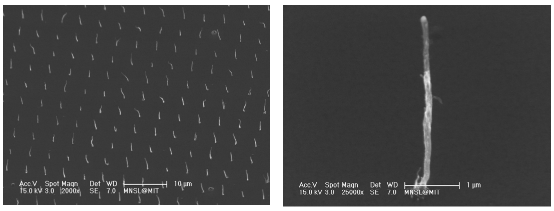


Figure 5 Subtractive nanopelleting processes.

The final step of the process is to transplant the released pellets to a new substrate (receptor wafer). We have successfully transplanted pellets onto an acceptor wafer surface as reported by the author [16]. A circular nanopellet has been made and then manually slid into a pre-patterned trapezoidal cavity. By fabricating nanopellets with embedded carbon nanotube bundles, we could prove the concept of transplanting assembly. Vertically grown carbon nanotube bundles can be relocated to an arbitrary location. This technology can be used to locally reinforce a composite structure by locating bundles of carbon nanotubes across the carbon fiber laminates.

If an individual carbon nanotube, instead a bundle, can be transplanted, more versatile nanostructures can be assembled with a high degree of freedom. In order to accomplish this goal, single strand carbon nanotubes need to be grown and embedded into high aspect ratio pellets. Prior reports have demonstrated that single strand carbon nanotubes grow on submicron sized nickel catalyst sites [14]. We have patterned submicron scale catalyst nanopatches using e-beam lithography and have grown single strand carbon nanotubes. Thin film nanodots of Ni/Ti (with diameters of 100 nm - 250nm, thickness 25nm/25nm) are deposited on a silicon substrate using electron beam lithography and electron gun metal evaporation. The patterning of nanodots is done by transferring CAD data to the E-beam lithography computer and exposing PMMA coated wafer to the E-beam by varying the aperture size, dose and electric field. After developing PMMA resist, evaporating Ni/Ti materials and performing lift-off processes, well patterned Ni/Ti dots are made. Then carbon nanotubes are grown in our plasma enhanced CVD machine. Figures 6 (a) and (b) show single strand carbon nanotubes vertically grown and spaced 10μm apart. The length of these tubes is 3 - 10 μm and 50-250nm in diameter. Process optimization is underway to grow single strand carbon nanotubes up to 5 μm long with various diameters.



a) b)

Figure 6 Single stranded CNTs grown vertically on patterned metal nanodots (a), a close up view (b)

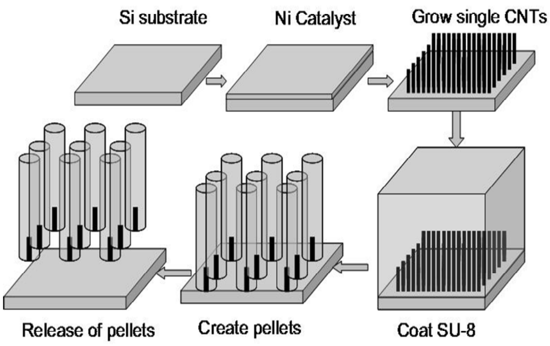


Figure 7 Additive nanopelleting processes.

In order to transplant single strand carbon nanotubes, they need to be embedded into high aspect ratio pellets (nanocandles). The subtractive processes described in Figure 5 is not adequate to make nanocandles, since the deposition of Ni/Ti nanodots at the bottom of the deep (20 μm to 50 μm) cylindrical trenches (5 μm in diameter) is not feasible with the existing E-beam lithography technology. In order to solve this depth of field problem, we have developed an additive nanopelleting process ("nanocandle process"). The key idea is to embed individual carbon nanotube into a high aspect ratio pellet after growing single strand carbon nanotubes on a flat substrate firstly where E-beam processing is feasible (Figure 7). The new additive process casts SU-8 polymeric layer onto a flat substrate where single strand carbon nanotubes are grown vertically on an array of Ni/Ti nanodots. Then the SU-8 layer is exposed to E-beam and developed to form nanocandles, which leaves high aspect ratio cylindrical blocks on each single strand carbon nanotube vertically standing on the flat Si substrate.

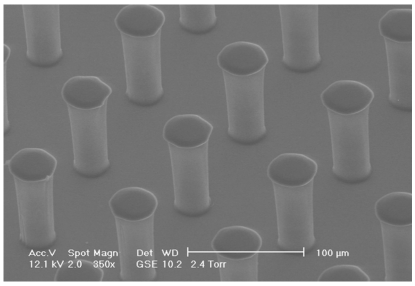


Figure 8 High aspect ratio polymer pellets formed on the patterned nanodots.

Figure 8 shows the high aspect ratio polymer pellets standing on the nanodots, where carbon nanotubes are not grown yet. When the single strand carbon nanotube process is optimized, individually standing carbon nanotubes will be embedded into the cylindrical pellets respectively. The embedded carbon nanotube can be later exposed to function as a nano-tip for applications such as atomic-scale scanning probes [18].

4 CONCLUSIONS

In this paper, Axiomatic approach for systems design has been used to develop less complex manufacturing processes for nanoengineering products. Axiomatic approach provides better understanding of the complexity in assembling products at micro-scale and guides to develop proper assembling technology for nanostructures. Though many nanostructures have been developed and found to be very useful, we have very little tools to assemble them to a multiscale system. This problem may be named as the *tyranny of scales*, since it is almost the same challenge we faced 50 years ago when the solid state transistor was invented but no proper method to assemble them was available. A method to assemble carbon nanotubes to deterministic locations is developed to have reduced amount of real complexity. In order to minimize the complexity, the common rage of the assembly process has been increased by moving the design range of handling carbon nanotubes to have larger overlap with the system range of the existing microfabrication processes. This was accomplished by embedding a bundle of CNTs or single strand CNT into a microscale polymer pellet. Until we find a new way of assembling nanostructures like proteins fold themselves, this idea of transplanting may provide a viable solution for nanostructure assembly.

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