Chapter 2
Design Framework for Micro and Nano-Scale Products

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Abstract The design and manufacturing of high quality micro-electromechanical systems (MEMS) is becoming increasingly complex as the manufacturing tools available diversify. Design of nano-scale products is even more complex. Small-scale products tend to have highly coupled designs, decoupled at best, because of the serial nature of fabrication, material and process constraints and lack of adequate fabricating processes. This paper proposes a structured design framework, which enables designers to achieve the correct functionality by either reducing the complexity in multi-scale manufacturing or by developing a new manufacturing process to circumvent the existing constraints.

2.1 Introduction

Products have grown into ever-larger multi-scale systems while their components have shrunk to a smaller-scale (i.e., micro and nanostructures). The design and manufacture of multi-scale products with newly developed materials (such as carbon nanotubes and graphenes) has become increasingly complex. Small-scale products are not realizable when engineers make bad designs. This paper aims to establish a design framework for micro- and nano-scale products where no structured framework for design has been readily available.

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A micro system can be characterized by small dimensions, either of the system/component itself (one or more critical dimensions) or of the functional features of the system/component [1]. Generally, two categories of micro products are identified: (1) components with at least two critical dimensions in the sub-mm range, (2) relatively large components with functional features in the μm range. If the characteristic length in the above is in the order of 100 nm or smaller, they become nano systems.

Microelectromechanical Systems (MEMS) technology has shown the potential to revolutionize the production of sensors and actuators. However, many industrial efforts have experienced significant delay in delivering products in time for market success. This is somewhat due to poor design of the devices and production methods, but is mainly due to the lack of delivering the functions customers want. A structured design framework is necessary to effectively guide designers for small scale products.

We propose that small scale products can be designed with the following three steps: (1) *Functional Design with Axiomatic Design Framework*, (2) *Reduction of Complexity,* (3) *Multi-domain Design Mapping*. Regardless of the scale of products, a good design should clearly define the functionalities of the product ("what we want") at the top level of the design process and ensure that they can be attained during and after the product development. Without a structured design framework, functional requirements may be misinterpreted or lost. Therefore the first and the most important step to make good small-scale product design is to search and generate the functions of the product and maintain them throughout the design process. Axiomatic Design has been a useful design framework for generating functional requirements and mapping them across the design domains.

Design of small-scale products tends to be complex because micromachining and nano processes involve specialized top-down or bottom-up processes and the cost of prototyping (or make and see iterations) is enormous. In order to predict the performances of these devices before prototyping, domain-specific computer aided engineering (CAE) tools and solvers are necessary [2]. Unlike the narrow and deeply studied integrated circuit (IC) products, however, MEMS product design must account for the interaction between electrical, mechanical, fluidic, chemical and optical forces among others, which makes it practically difficult to develop general CAE tools for MEMS. Furthermore, CAE tools alone cannot help to reduce the complexity in coupled designs. Therefore, the second step of the small scale product design is to understand the nature of complexity in small-scale product design and to find ways to reduce it.

In evaluating the complexity of a MEMS device the designer is presented with the challenge of determining which manufacturing processes are best suited to meet the system's functional requirements and the sequence of those interdependent processes. Compounding the difficulty, MEMS design requires integrating an understanding of the coupled nature of the manufacturing tools into the design process. Design for manufacturing rules of thumb are commonly used to ensure manufacturability in macro scale products. These rules are often process or design specific such as radiusing internal corners on milled parts or depositing materials with higher processing temperature first in thin film deposition. It is unclear then, how a designer who is attempting to discover the best process or sequence would be able to make use of such rules. What is needed is a way for MEMS engineers to understand the impact of process changes on device functionality during the design phase. Axiomatic Design is a useful tool for this because it provides a structured basis for mapping design parameters to process variables as well as to understand the impact of the process variables on the functional requirements. Sometimes, this effort can lead to a novel manufacturing process, which uncouples the design couplings with the existing processes.

Three short case studies are presented to demonstrate how each step could be accomplished.

2.2 Functional Design is the First Step

A successful MEMS product, like macro-scale products, must align a functionally uncoupled or decoupled design with processes that ensure reliable manufacturing. Axiomatic Design is a useful tool for this because it provides a structured basis for generating functional requirements and mapping them across the design domains.

Axiomatic design was developed in the late 1970s by Prof. Nam Suh at MIT offering two axioms that provide a framework for the decision-making and the mapping between "what we want (function requirements)", and "how we can achieve them (design parameters)" [3, 4]. Originally the method was developed for managing the design process for complex engineering products and systems but is extended nowadays to a broad range of systems (for example in healthcare or lean systems applications [5]).

Axiomatic Design (AD) approach is based on the distinction of four different design domains: Consumer domain, Functional Domain, Physical Domain and Process Domain. The Consumer domain is where customer's needs reside. These customer's needs must be mapped into the functional domain and translated into a set of functional requirements. The functional requirements (FRs) are defined as the minimum set of independent requirements that characterize the design goals. These FRs are then mapped into the physical domain, where the design parameters (DPs) are chosen to satisfy those FRs. The AD process can be summarized as shown below:

1. *Conceive the top level FRs.*
2. *Map FRs to Design Parameters DPs at the same level.*
3. *Mapping process can be analysed/evaluated with the two design axioms to ensure a good design.*
4. *Above steps* (1–3) *are repeated top to down in a zig-zag manner until the physical solution can be conceived from the mapped DPs.*
5. *If all the FRs reach leaf nodes* (*where the conceived FR-DP is clear and no further decomposition is necessary*), *physical integration of them to a feasible solution will lead to the final design solution.*

The first axiom—the so-called Independence Axiom—requires an uncoupled or at least decoupled design, which guarantees independent control of the functionality of the product. The FRs must be translated into DPs without affecting other FRs. That means the set of DPs has to be chosen so that they satisfy the FRs as well as maintain their independence [4].

The information axiom (the second axiom) makes it possible to benchmark different design alternatives by comparing the overlap of the design range which is required to fulfill the product's functionality and the system range that the different design options offer. The design, which offers the lowest information content, that is the design with the highest probability of success, will be selected.

Here a case that demonstrates how a new MEMS product is designed by defining the top-level functional requirements at the early stage of design.

Case 1: **Design of Piezoelectric Ultrasonic Micro Transducer**

Advanced medical ultrasonic imaging and fast 3-D scanning systems, operating in both transmit and receive modes, can be achieved with tiny 2-D arrays of transducers with piezoelectric ceramics. However, the labor-intensive manufacturing processes, such as dicing, bonding, and delicate assembly of crystallized piezoelectric ceramic limit the production yield, rate, and quality. Piezoelectric Micromachined Ultrasound Transducers (PMUTs) would offer several advantages to the conventional bulk machined ultrasonic sensors, including batch fabrication, electronics integration, and better acoustic matching to the surrounding medium [6]. Most of all, it can be formed into a 2 dimensional (2D) array for 3 dimensional (3D) imaging which will enable advanced medical imaging capability such as intracardiac echocardiography. The goal of this design is a tiny 2-D array of piezoelectric ultrasound transducers that enable ultraportable and high power ultrasound imaging systems. Top-level functional requirements were searched to achieve this goal and the matching design parameters were explored to make the design uncoupled or at least decoupled.

A typical PMUT is composed of a suspended membrane, made up of a structural silicon layer and a piezoelectric layer sandwiched between two metal electrodes. The membrane is clamped at its edges, resulting in reduced device acoustic impedance. With the application of an AC voltage across the piezoelectric layer, the membrane vibrates as a result of the strain mismatch between the elastic layer and the piezoelectric layer. Most PMUTs operate with a pulse-echo in the range of 1–16 MHz, where the optimum operating frequency is chosen based on the required depth of penetration, resolution, and tissue composition. A typical ultrasonic device for medical applications operates at a resonant frequency of 3 MHz (FR1), which can be controlled by varying the membrane radius as well as the membrane thickness (DP1). It is not easy, however, to achieve the precise resonant frequency of the membrane due to manufacturing tolerances. Intentional residual stress on the membrane can be used tune the resonant frequency as well to correct for any manufacturing tolerance. Precise resonant frequency (FR2) is thus provided by the tuning ring on the membrane (DP2). The output acoustic pressure is directly proportional to the membrane displacement and deflection shape, where

Table 2.1 Top-level functional requirements (FR) and the design parameters (DP) of PMUT for medical imagining application

	Functional Requirements (FR)	Design Parameters (DP)
1	Resonant frequency of 3 MHz	Membrane thickness
2	Tunable center resonant frequency of 2 MHz	Voltage applied to an external tuning ring
3	Membrane Deflection: 0.1 μm	Membrane radius
4	Deflection Shape: piston-like	Corrugation edge design
5	Impedance matching to external environment	Membrane stiffness
6	Cross-talk between elements	Elastomeric material separating elements

a 10 nm average membrane displacement generates roughly 1 MPa. For high acoustic power applications such as brain imaging, about 100 nm membrane deflection is needed (FR3). The applied voltage level, the membrane radius, as well as the membrane thickness would control the membrane displacement. We chose membrane diameter as the DP3. The AC voltage that drives the membrane can be used to control the membrane displacement, whereas optimized values of the membrane radius and thickness can be used to control the resonant frequency in order to achieve a decoupled system. A piston-like membrane motion (FR4) is desired to increase the displaced volume, and is realized by attaching the membrane via a corrugation to the fixed support (DP4). In order to maximize the energy transfer to the surrounding, the membrane impedance (FR5) should match the acoustic impedance of the surrounding medium. Changing the membrane stiffness (DP5) or depositing a layer on top of the membrane can adjust the membrane impedance. Separating the elements (DP6) with a polymeric foundation will minimize the cross talk between the elements (FR6). Table 2.1 summarizes the functional requirements and the design parameters of the PMUT generated. The proposed top level FRs and DPs shown in Table 2.1 make an uncoupled system which resulted in a US patent pending design.

The process of codifying functional requirements and design parameters not only identifies possible couplings, but also ensures clear focus on successfully satisfying critical requirements. This way of expressing a design also serves as a basis for complexity analysis and multi-domain design. Defining a comprehensive set of independent functional requirements is therefore a key part of the proposed design framework.

2.3 Step Two: Reducing the Complexity

Nano science has found many interesting nano structures with novel potential functions in real world applications. However, nano products require an integration of nano-components to macro systems and the degree of complexity is very high when nano structures are integrated (or assembled) to macro products. Success of small-scale system design depends on better understanding complexity and subsequent reduction of complexity in assembling multi-scale components into a functioning system. There have been many different views and approaches to understanding complexity in the fields of information technology, system biology, mathematics, meteorology and economics among many fields of science. Algorithms to find out absolute measures of complexity, however, have not been well established. In this paper, complexity of small-scale system design is understood though the axiomatic design framework.

A relative measure of complexity has been introduced by Suh [7]. In his complexity theory, complexity is defined as a measure of uncertainty in satisfying the functional requirements (FRs) within the specified design range. There are subtle differences among the uncertainty, complexity and difficulty which all provide hardship in design. Since it is believed that design axioms have been always true and no counter examples have been observed yet, we may define complexity as a result of a design's failure to conform the design axioms. Complexity can be defined as a collective outcome when a design doesn't satisfy the design axioms. The four kinds of complexity can be explained by their causal nature with respect to the design axioms.

– *Time-independent real complexity*: when a design is coupled. (Independence axiom violation)
– *Time-dependent periodic complexity*: when the coupled nature of design is capsulated to prevent the propagation across the system.
– *Time-independent imaginary complexity*: when a design is decoupled and not solved in the particular sequence (lack of knowledge).
– *Time-dependent combinatory complexity*: when a design has many states (FRs, DPs), which are not at equilibrium and change as a function of time (non-equilibrium).

The above speculation about complexity can be applied to small-scale systems design in that a coupled design with the high scale order will become extremely complex. When the scale order is high, all of the four types of complexity become larger. Suh suggested functionally periodic systems have a smaller scale complexity when the complexity is divided and confined in functionally uncoupled spatial/temporal sub-domains. Functional periodicity by dividing the system into sub-domains can be applied to micro and nano product designs in order to reduce and confine complexity. A new assembly process for carbon nanotubes has been developed based on the above framework to reduce the system complexity.

Case 2: **Reduction of Complexity by Reducing the Scale Order**

Assembly of individual nanostructures in a deterministic manner has been a big challenge due to its complexity. This case demonstrates a new method of handling and locating individual carbon nanotubes (CNTs) and integrating them into microelectromechanical systems (MEMS). An effective method of CNT assembly was demonstrated by reducing the complexity of assembly. It provides MEMS designers with the ability to locate an individual CNT nearly arbitrarily for the first time [8].

The key idea of transplanting assembly is to grow the vertically aligned individual CNTs on a substrate at ideal growth conditions and to transfer well-grown CNT strands to the target locations via micro-scale CNT carriers. The major technical issues solved are: (1) how to grow vertically aligned single strand CNTs at predefined locations, (2) how to preserve/control the orientation/length of an individual CNT during transplanting processes, and (3) how to locate/release an individual CNT at the target location. This assembly concept transforms the scale of tools necessary for CNT assembly from nano-scale to micro-scale, which enables manual, automated or parallel assembly of individual CNTs to MEMS in a deterministic and reproducible way.

The first step in transplanting assembly is the vertical growth of CNTs, which requires seeding catalytic nickel nano-dots at predefined locations on the Si substrate. An array of Ni catalytic dots (100–200 nm in diameter and 30 nm in thickness) was defined using electron beam lithography followed by metal deposition and liftoff process. An array of vertically aligned CNTs was grown using a home-built plasma enhanced chemical vapor deposition machine. Each CNT strand was then embedded into a micro-polymer block, which serves as a CNT carrier. A double polymeric layer encapsulation process was used with SU-8 as the top layer and polymethylglutarimide (PMGI) underneath. The SU-8 block (15 μm in thickness and 20 μm in diameter) forms the body of the carrier, while the PMGI layer (1.5 μm in thickness) holds the body until the release of the carrier from the substrate and then is removed to expose the CNT tip. The orientation of the embedded CNT is near parallel to the axis of the SU-8 block. The diameter of CNTs matches the size of Ni dots, and the length is 5–10 μm with a uniform cylindrical shape. The thickness of the bottom PMGI layer was chosen to be 1.5 μm so that a target aspect ratio of the exposed CNT tip is about 10–1. The 20 μm SU-8 blocks can now be used to manipulate and move the CNT to the desired location.

This technique was used to manufacture a CNT tipped atomic force microscope (AFM) cantilever with a unique ability to resolve high aspect ratio features as shown in Fig. 2.1. It is shown in this case decomposing the system into smaller uncoupled micro-domains can reduce the complexity. The scale order reduction of a multi-scale system into smaller-scale periodic systems can reduce the complexity of the whole system and subsequently ensure a good design and manufacturing by generating functional periodicity as was proposed in the complexity theory.

2.4 Step Three: Multi-domain Mapping

MEMS designers face an increasingly complex set of choices when selecting manufacturing processes. Furthermore, because the manufacturing processes often drive the designs of micro-systems used, the impact of process selection must be understood early in the design process.

Mapping design parameters to process variables early on in the design phase can provide information about the processing tools likely to be used and their limitations. Often with MEMS design, the impact of manufacturing process selection is apparent after only a few levels of decomposition. With this information the designer can evaluate the impact of process decisions on FR-DP

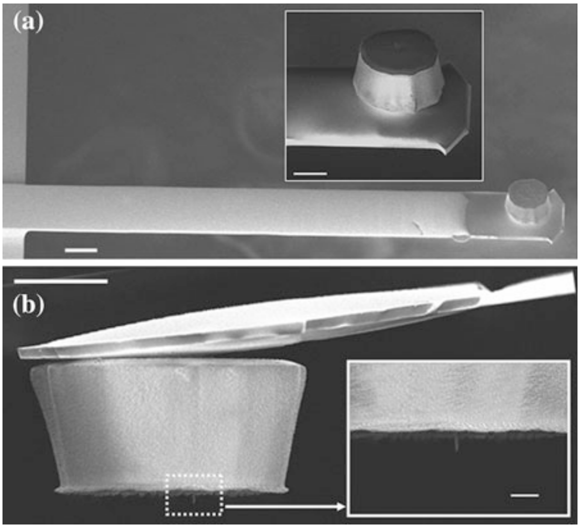


Fig. 2.1 CNT tipped AFM probes, scale bars 20 μm (**a**), 10 μm (**b**), 2 μm (inset) [10]

coupling. If processing constraints are not considered carefully, and instead DPs are selected based on intuition or previous experience, it is possible for functionality of the design to be sacrificed due to perceived limits on manufacturing processes. Using multi-domain design, it becomes apparent when a process improvement may enable a new DP and remove functional coupling. With this analysis method, the designer is able to evaluate whether functional coupling or process coupling is limiting the functionally of the product and to focus development effort appropriately.

Case 3: **Improving Process Flexibility by Ink Jet Printing**

Thin film lead-zirconate-titanate (PZT) is an attractive material for piezoelectric MEMS due to its high coupling coefficients. Manufacturing limitations have thus far limited wide commercial application of this material. For this case, we studied the couplings inherent to PZT deposition and tried to eliminate them.

Many methods of depositing thin film PZT have been demonstrated including sputtering and laser ablation. However, the most common PZT deposition method is sol–gel spin coating which achieves high quality films at low cost. Analysis of the forward and backward couplings of process variables helps identify what process changes might most significantly affect device performance [9]. Through our work spin coating PZT, we became aware of a significant, irresolvable coupling between the spin coating process and device structural layer.

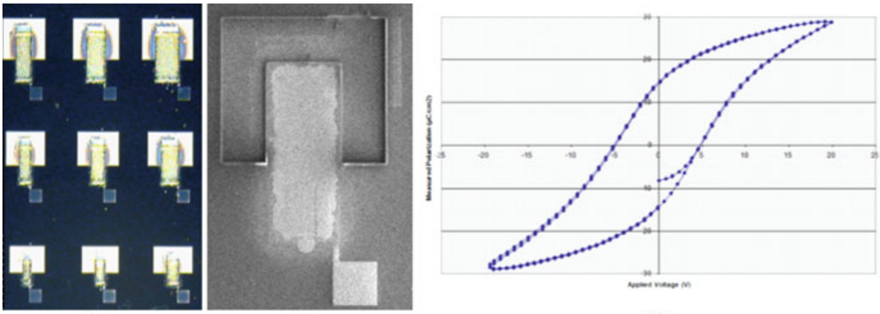
The thermal processing of solution deposited PZT causes large tensile stresses in the final film. It is not possible to spin coat PZT over even small out of plane features without significant cracking. This causes current leakage or shortage and deteriorates performance. This forward coupling from device geometry limits device designs to planar geometries. One way to eliminate this coupling is to sequence the process such that the PZT is deposited before the formation of the structure. This has been demonstrated but requires either carrying the fragile PZT through a micromachining process, or using an additive process which requires compromising on material properties [10, 11]. A better, fully uncoupled, approach is to create a more flexible way of depositing the PZT precursor.

Recently, direct write methods have been shown to be a viable alternative to standard lithographic processing of MEMS [12]. Digital fabrication of solution-based PZT via drop-on-demand printing has the potential to remove many of the process constraints of spin coating, while maintaining all the advantages of a chemical solution deposition method. It provides for as deposited patterning, coating on or around arbitrarily out of plane features, and deterministic thickness control. A new process of depositing PZT, based on printing, was developed that may enable new process sequencing and therefore improved device performance.

Several experiments were conducted in order to realize this drop-on-demand based deposition method. Solutions were formed from a Mitsubshi 50/49 PZT sol–gel (E1) based on butyl alcohol and propylene glycol. As purchased, this sol is 85 %(wt) solvent and 15 %(wt) a mixture of lead, zirconium, and titanium metal oxides. Combinations of 2-methoxyethanol, isopropanol, and propylene glycol were added to the sol to create the diluted PZT inks. To prevent clogging of the printer nozzle and defects in the film, sources of particle contamination in the solution and in the environment were addressed and controlled. Throughout this work, over thirty ink chemistries, with dilution levels ranging from the as-purchased 15 %wt of metal oxides down to 2 %wt, were tried and the levels of dilution require for stable printing were observed. Preventing clogging also requires controlling the evaporation rate of the ink. If the solvent evaporates too quickly, metal organic molecules are built up inside the nozzle and firing chamber and concentrations that exceed stable printing requirements result. Maintaining a flow through the nozzle at all times prevents this type of clogging.

Controlling the distribution of solute material on the substrate after drying is also critical for uniform deposition of high quality films. The diffusion of solutes towards the film edges during solvent evaporation known as the coffee stain effect can lead to significant non-uniformity. In order to overcome this non-uniformity a study was conducted to determine the ink volatility and substrate temperature required to achieve the optimum level of spreading and diffusion.

After optimization of solution chemistry and substrate temperature, PZT films between 100 and 500 nm with less than 40 nm variation could be printed with a droplet size of 80 pl. Spot sizes as small as 43 μm were achieved with a 10 pl droplet of PZT ink deposited on a platinum substrate. The edge variation of printed lines was controlled within ± 10 μm. The ability of this new process to impact process sequencing was demonstrated through the deposition of PZT on pre released test cantilevers (Fig. 2.2). Analysis of forward and backwards couplings that exist due to process limitations highlighted the improved functionality that could be achieved by eliminating those couplings. When a MEMS designer properly understands the level and direction of process couplings, effort may be focused on process improvements that relive these couplings. As a result new geometry and material DPs become available and improved device performance may result.



(a) (b) (c)

Fig. 2.2 **a** An array of PZT cantilever resonators (PZT printed after geometry formation). **b** Detail of a single PZT cantilever. **c** Polarization vs. voltage data from a printed PZT film

2.5 Conclusion

The complexity of small-scale products can originate from the functionally coupled designs and/or the high scale order of their manufacturing processes. A three-step design framework is proposed to cope with the complexity and to minimize the costly iterations in micro/nano product development. Three case studies demonstrate how this framework can be applied. Top-level functional requirements in developing a tiny 2-D array of piezoelectric ultrasound transducers were explored and investigated to make the design uncoupled or at least decoupled. A new nano-assembly process for carbon nanotubes has been developed by periodically dividing the complexity associated with the scale order. Finally a multi-domain design analysis approach was used to show how process decisions might impact device functional requirements.

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