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Materials Issues for Micromachines Development - ASCI Program Plan

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Abstract Follows

Abstract

This report summarizes materials issues associated with advanced micromachines development at Sandia. The intent of this report is to provide a perspective on the scope of the issues and suggest future technical directions, with a focus on computational materials science. Materials issues in surface micromachining (SMM), Lithographie-Galvanoformung-Abformung (LIGA: lithography, electrodeposition, and molding), and meso-machining technologies were identified. Each individual issue was assessed in four categories: degree of basic understanding; amount of existing experimental data; capability of existing models; and, based on the perspective of component developers, the importance of the issue to be resolved. Three broad requirements for micromachines emerged from this process. They are: 1) tribological behavior, including stiction, friction, wear, and the use of surface treatments to control these, 2) mechanical behavior at microscale, including elasticity, plasticity, and the effect of microstructural features on mechanical strength, and 3) degradation of tribological and mechanical properties in normal (including aging), abnormal and hostile environments.

Resolving all the identified critical issues requires a significant cooperative and complementary effort between computational and experimental programs. The breadth of this work is greater than any single program is likely to support. This report should serve as a guide to plan micromachines development at Sandia.

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Executive Summary

Components based on microsystems technologies, such as micromachines, microelectronics, optoelectronics, sensors, and photonics, are expected to play a critical role in extending the life of the weapons stockpile. Sandia is currently developing manufacturing capabilities in several micromachines technologies including surface micromachining (SMM), Lithographie-Galvanoformung-Abformung (LIGA: lithography, electrodeposition, and molding), and meso-machining. In each of these areas, materials issues play prominent roles in the design, fabrication, performance, and reliability of the devices. The development of engineering solutions to these issues can be significantly accelerated by exploiting Sandia's existing materials modeling expertise, much of which has been developed through the ASCI Materials Program.

This document presents an assessment of the most important materials issues in micromachines. The goal is to provide the foundations for a new strategic plan to divert the resources of the ASCI Materials Program towards micromachines development. This process began with input from an interdisciplinary team consisting of key micromachines developers, materials scientists, and computational model developers at Sandia. Materials issues were identified for SMM, LIGA and meso-machining. Each individual issue was then assessed in four categories: degree of basic understanding; amount of existing experimental data; capability of existing models; and, based on the perspective of component developers, the importance of the issue to be resolved. Finally, results were compiled and summarized into tables. By applying appropriate objective criteria for prioritization, these summary tables of materials issues can be used to identify critical technical directions and determine reasonable allocation of resources.

Three broad requirements for micromachines emerged from this process. They are: 1) tribological behavior, including stiction, friction, wear, and the use of surface treatments to control these; 2) mechanical behavior at the microscale, including elasticity, plasticity, and the effect of microstructural features on mechanical strength; and 3) degradation of tribological and mechanical properties in normal (including aging), abnormal and hostile environments. While existing materials modeling capabilities can address some aspects of these issues, there is also a great need for better understanding and development of new computational tools.

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Introduction

Microsystems technology has been identified as important for future weapon refurbishment[1]. This technology allows components and systems to be built with fewer piece parts but more functionality. Thus it can enhance the surety of weapons as required by the Stockpile Life Extension Program (SLEP) schedule. The proposed MESA facility will provide an integrated engineering environment to support the development of microsystems, including micromachines, microelectronics, optoelectronics, sensors, and photonics, and to reduce the cost and 'research-to-production' cycle time in the system development. However, because microsystems technology is a relatively new and revolutionary field, much additional work, ranging from process control to component performance and reliability analysis, is needed to qualify its use for weapon applications.

Among this additional work, as described in the Integrated Microsystems Roadmap[2] at Sandia, there are many materials issues that need to be addressed. These cover many science and engineering areas in the full life-cycle of the systems. A few examples are: fabrication and manufacturing processes, performance analysis, and reliability studies to ensure that weapons remain functional and safe under STS (Stockpile-to-Target Sequence) environments.

Computer-based modeling and simulation will play a central role in the proposed integrated engineering environment. This is described in more detail in Appendix A: An Integrated 'Design-to-Visualization and Analysis' Infrastructure for Microsystem Development. The flowchart in Figure A.1 illustrates a proposed model-based infrastructure for "design-to-visualization & analysis."[3] One critical component in this flowchart is "physical information." The purpose of this component will be to provide a complete quantitative description of the relevant physical characteristics of the microsystems components. The scope will include all stages of the component life-cycle, starting with the manufacturing process, and including deployment, aging and end-use performance and reliability.

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[1] "The Microsystems and Engineering Sciences Applications (MESA) Program Plan", Sandia National Laboratories, September 30, 1999.

[2] "Integrated Microsystems Roadmap", developed under charter of the Electronics Science & Technology Council, S. T. Picraux, et al., May 13, 1996.

[3] "Possible ASCI Program for Microsystems Development", Sandia memorandum, C. C. Wong, et al., November 30, 1999.

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Goal

Sandia has long been invested in computational materials science, including methods development, companion parallel algorithms, and multi-length-scale modeling. In recent years, much of this capability has been developed within the ASCI Materials Program. Figure 1 illustrates how computational materials modeling has become an integral part of DOE's science based stockpile stewardship program.

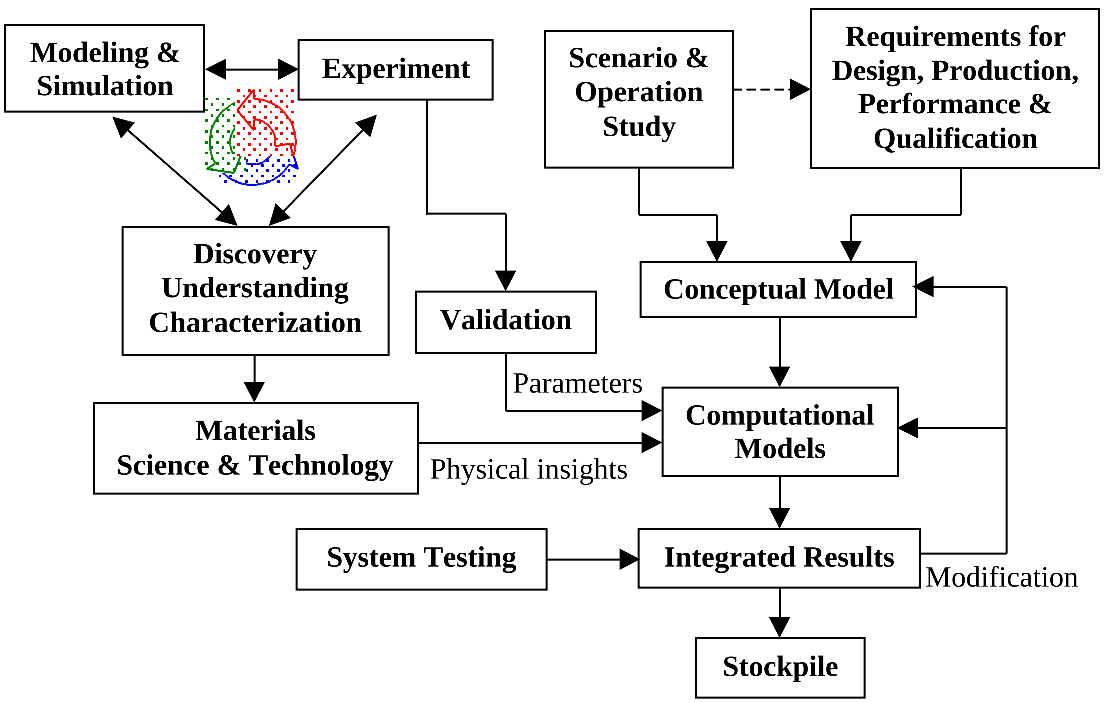

Figure 1: Computational materials modeling and simulation with experimental validation enhances Sandia's Materials Science and Technology (MS&T) expertise which is integrated into the DOE/ASCI program for Science Based Stockpile Stewardship.

In order to assess how best to apply this capability to the needs of microsystems in general, and to micromachines development in particular, an interdisciplinary team was formed, including many of Sandia's key micromachines developers and materials modelers. The goal of the team was threefold: 1) to identify a comprehensive list of materials issues important to the processing, performance and reliability of weapons micromachines; 2) to identify the high-priority issues of these using an objective evaluation system; and 3) to develop a strategic plan for focussing ASCI resources on the high priority issues.

The first two goals have been accomplished. This document summarizes the results of the process. It also lays the foundation for accomplishing the third goal. Existing ASCI capabilities which can be applied to the high priority issues are reviewed, and areas requiring further development are identified.

Materials Issues

Because mesoscale and microscale fabrication and manufacturing technology has advanced rapidly in various areas in the past few years, there may be many ways to present and discuss the materials issues. In this report, the materials issues are catalogued by the existing fabrication technologies: surface micromachining (SMM), which is mostly silicon based; Lithographie-Galvanoformung-Abformung (LIGA) process, which covers metal, ceramics, polymer; and meso-machining techniques such as laser ablation and micro-electro discharge machining (micro-EDM) for stainless steels, rare magnet and ferrite materials, kovar, ceramics, and glass.

This study began with input from an interdisciplinary team of key micromachines developers, materials scientists, and computational model developers at Sandia. Materials issues were identified for SMM, LIGA and meso-machining, respectively. Each individual issue was then assessed in four categories: degree of basic understanding; amount of existing experimental data; capability of existing models; and, based on the perspective of component developers, the importance of the issue to be resolved. Finally, the results were compiled and summarized into tables.

Below is a short summary of the most important issues for each of the three technologies followed by a selection of issues common to all three areas.

Surface Micromachining (SMM)

Surface micromachining involves the deposition and etching of structural and sacrificial layer films to create micromechanical structures. It is a completely batch fabrication process, leveraging the existing manufacturing technology developed in the microelectronics industry. These structural and sacrificial layer films are grown on silicon wafers by either low-pressure chemical vapor deposition (LPCVD) or laser deposition. Usually the structural layer is polycrystalline silicon and the sacrificial layer is silicon dioxide or epitaxial silicon. Other materials such as silicon nitride, silicon carbide, amorphous diamond, and metals may be used in the process.

Materials issues important to SMM are listed in Appendix B. Because of the very small length scales (~1-10 μm), the influence of inertial force is secondary and surface interactions are of primary concern. When there is contact between parts, the adhesive, frictional, and wear properties affect the operational performance of devices and systems, both immediately after fabrication, after periods of operation, and after prolonged periods of inactivity. In regions of no contact, materials information such as the ranges of Young's modulus, residual stress, strain gradient, fracture strength, and coefficient of thermal expansion are important. Therefore micromachines can be designed to preclude stiction due to unexpected deflection and deformation, optimizing micromachines performance. Predicting the performance of electrostatically actuated devices using coupled electrostatic-deformation finite element models has also proven to be difficult, and improving these predictions will aid in design and provide another tool for analyzing and mitigating failure modes.

LIGA

LIGA is an acronym derived from the German words for lithography (Lithographie), electrodeposition (Galvanoformung) and molding (Abformung). It is a form of additive processing involving deep x-ray lithography of a sacrificial mold. The desired component is obtained by eloctrodepositing metal into the mold. The mold is dissolved after plating. The sacrificial mold is formed from a thick layer of polymethyl methacrylate (PMMA) which is bonded to a metallized silicon wafer. The PMMA layer is patterned by exposing it to high-energy x-rays using an absorb mask. The exposed regions are then removed using a high-selectivity solvent. The LIGA approach enables batch fabrication of components with nearly arbitrary in-plane geometry at thicknesses up to several millimeters while maintaining submicron dimensional control. Nickel, copper, and nickel/iron alloys are the most widely used LIGA materials, because of their excellent electrodeposition characteristics. However, the approach can also be extended to a wide range of materials, including other metals, plastics, ceramics, and composites.

Materials issues important to LIGA are listed in Appendix C. The larger length scales of LIGA components reduce the impact of surface interactions. Of greater importance is process-induced variability, and process limiting materials properties. For example, spatial variation in current density can result in non-uniform mechanical properties within a single component and also within a single batch. Furthermore, poor adhesion between the PMMA and the metallized wafer limits feature sizes and greatly reduces batch yield. There is also great interest in extending the materials suite to produce components with very specific physical properties, such as high magnetic susceptibility. A very detailed and comprehensive list of needs for LIGA in process science and performance science can be found in the white paper "LIGA Science Needs," prepared by Jill Hruby (8702), *et al.* at SNL/CA.

Meso-machining

Development of mesoscale machining technology is a manufacturing initiative from Center 14100 to bridge the gap between micro and miniature machining. Its technologies include focused ion beam, micro-milling and micro-turning, excimer and femto-second laser, and micro-electro discharge machining (micro-EDM). This report will focus on laser micromachining and micro-EDM.

Materials issues important to meso-machining are listed in Appendix D. For both micro-EDM and laser ablation, rates of mass transport and heat transfer during material removal can greatly influence product quality. For laser ablation, the influence of the laser-induced shock wave on the materials properties and long term damage are also poorly understood. For micro-EDM, controlling the wear rate of the electrode tip during machining is essential for good product uniformity.

Common Issues

While each of these technologies presents its own unique set of challenges, the most important issues tend to be common to all the technologies, albeit with varying severity. We have summarized the most important of these below.

Adhesion/Friction and Wear

Because of the very high surface to volume ratios of micromachines components, surface mechanics and tribology dominate the mechanical dynamics. In the worst cases, opposing surfaces can become physically bonded, resulting in stiction. Even without stiction, frictional forces can be very sensitive to microscale roughness and to the size, shape, and distribution of individual asperities.

Environmental and Aging Effects

In order for micromachines to be certified for weapon applications, their behavior in normal (including aging), abnormal, and hostile environments must be understood and quantified. Degradation of component performance over time is inevitable. The challenge is to maintain an acceptable level of performance over some long time period, after which replacement or refurbishment must be carried out. In the case of micromachine components, performance degradation can be caused by a variety of mechanisms and processes, many of which are poorly understood. For example, surface properties can evolve over time due to environment, microstructural changes, mass diffusion, and/or wear.

Dimensional Metrology

Routine methods to make precise in situ measurements of component dimensions do not currently exist.

Mechanical and Physical Behavior

The most important bulk properties for LIGA are yield strength, toughness, elastic modulus, and magnetic behavior. Those for SMM are elastic modulus, stress gradient, and residual stress. Isotropic continuum models might be unreliable for representing the mechanics when feature size and microstructural dimension are comparable. In addition, the electrodeposition in LIGA and the CVD process in SMM produce columnar microstructures, typically involving large lenticular grains oriented parallel to the deposition direction. The effects of textured grain structure on elastic-plastic behavior, friction, wear, and fracture at the microscale are not well understood. For both LIGA and SMM, mechanisms of damage development in abnormal and hostile environments are also unknown.

Coatings/Surface Treatments

Control of surface characteristics is essential to the performance and reliability of micromachine components. A variety of surface modification techniques exist and their primary function is to control adhesion and friction. In all the techniques, it is desired to create a uniform, highly durable, topology-independent coverage with minimal dimensional change. In SMM, self-assembled monolayers (SAMs) present immense opportunities, but also have many obstacles. In LIGA, the most success has been achieved using metal implantation, but currently this is only limited to line-of-sight surfaces.

Exploitation of ASCI Materials Resources

Existing Capabilities

Over the last several years, the ASCI Materials Program has supported the development of a range of massively parallel simulation codes, some of which can be directly applicable to materials issues in microsystem-based devices. These are summarized briefly below.

Mesoscale Modeling and Codes

- PARGRAIN: 3-D microstructure evolution simulation using the Monte Carlo Potts model
- GLAD: Lattice-based linear elastic simulation for brittle cracking and failure in 3-D grain structure using a ball-and-spring model
- MPM: Continuum-based meshless simulation for polycrystalline plasticity, crack initiation and inter/intra-granular cracking in evolving 3-D microstructure
- Par-Phasefield: 3-D grain growth simulation using continuum-based phase-field models
- JAS3D: Finite-element structure mechanics simulation for stress/strain distribution in polycrystalline materials and surface interactions (e.g. friction, adhesion)
- Tahoe: 3-D finite element code for modeling crack growth

Atomistic Simulation and Molecular Theory

- SIGNATURE: Linear-scaling algorithm for generation of large atomistic structure models
- LAMMPS: Molecular dynamics simulation of adhesion, polymer transport, and self-assembly of monolayer
- PRISM: Molecular theory calculation of structure, gas solubility and adhesion for polymers
- TST code: Linear-scaling calculation of transition states for transport in amorphous polymers

Ab initio Solid State

- QUEST: Calculations of phase diagrams, elastic modulus, and diffusive transport rates

Others

In addition, many other capabilities have been developed outside the ASCI Materials Program which may be well suited for addressing some issues. As such they should be considered for ASCI Materials Program funding. Examples include:

- LADERA: Grand Canonical Monte Carlo Molecular Dynamics (GCMCMD) for direct simulation of steady state molecular transport in fluids, polymers and nanoporous materials
- TRAMONTO: Non-local classical density functional theory for equilibrium structure of fluids at interfaces. Applications include adsorption, capillarity, surface templating, and self-assembly, etc.
- EAM: Atomistic calculations using the embedded atom method for materials properties.

Development Needs

Micromachines technology development encompasses a large number of materials issues as presented in this report. Some of the tools listed above will be directly applicable to this new and challenging field. Many other approaches may also prove effective. Rather than an exclusive set of approaches, this report focuses on some examples of areas where opportunities might exist.

As mentioned earlier, surface interactions in MEMS devices and materials strength in LIGA parts are the two major technical challenges. The ASCI Materials Program has already developed a strong capability in modeling adhesion strength using molecular dynamics simulations (LAMMPS). However, the original ASCI work is focused on tensile strength only. In the case of micromachines, shearing mechanics (friction and wear) are as important as tensile behavior. This will require a significant modification of focus and also implementation of new simulation methodologies, as well as the consideration of new effects, such as surface asperities. The ASCI Materials Program has developed simulation capabilities that span the atomistic to continuum scales, and together these methods can be used to help develop improved interfacial models for qualifying microsystems.

Modeling of materials strength will require a better representation of the mechanics of complex microstructures, particularly in the case of LIGA components. This is less critical in the case of SMM, as the polysilicon undergoes brittle failure, and can be well described by existing linear-elastic models (GLAD, MPM, and Tahoe). However, for predicting the mechanical behavior of the materials and the performance of both LIGA and SMM devices, it is important to build a database of information because length scale issues that violate the postulate of locality are expected to arise during the finite element analysis. Currently, there is no simulation code that can handle finite element analysis at the length scale of the micromachines that Sandia is developing. A long term project to implement nonlocal materials models in appropriate simulation codes, and then verify and validate their use for designing and analyzing microsystems based components, should be considered.

For optical MEMS devices using LIGA, x-ray photochemistry is of critical importance to the smoothness of vertical surfaces. One approach is to apply molecular simulation methods that incorporate both photochemical reactions and an atomistic description of the PMMA structure. This approach can be used to determine the impact of an x-ray source on the PMMA structure, and the influence of processing conditions on the sidewall roughness. This computational study of materials processing will help build better and more reliable materials for the Enhanced Surety Program.

Sandia must ensure weapon components performance for longer than 30 years of life. The inclusion of micromachines into these components demands that an understanding of aging and reliability of these devices be obtained. Such understanding and predictive capability is a very challenging task. Associated experimental programs are essential to the success of the modeling effort, and must be conducted concurrently. It is critical to initiate a joint modeling and experimental project to characterize and quantify aging issues associated with not only friction and wear but also operation after many years of dormancy. Due to the nature of aging processes, such a project may take several years to develop tools that can be used with confidence to make an impact on the design process. Therefore, forming the project team and planning the tasks should start as early as possible.

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Appendix A

An Integrated ‘Design-to-Visualization and Analysis’ Infrastructure for Microsystem Development

(with input from 1100, 1700, 8700, 9100 centers)

Point-of-Contact: C.C. Wong

Overview

Recent developments in microsystems technology at Sandia have demonstrated the feasibility of this technology for future weapon applications. However at the present stage, the microsystem technology is not mature enough to be seriously considered for the refurbishment of weapon components. Further development is needed to address various issues in fabrication, device performance, and reliability. Some of these issues are well documented in the “Microsystems Product Realization Plan” by Sam Miller and David Plummer, dated July 26, 1999. More general science and technology issues regarding microsystems for weapon applications are currently being developed at Sandia (POC: Gil Herrera, 1812). The ASCI applications program can help to make this microsystem technology ready for Full Scale Engineering Development (FSED) by building modeling and simulation capabilities that address the critical needs in microsystem development.

The critical needs can be divided into two phases. Phase 1 addresses product realization and phase 2 is for device qualification. Production realization involves developing appropriate design realization capabilities, as well as developing precise, reliable, and consistent fabrication processes which lead to high quality, reproducible components. It is a challenge to meet this goal because of the complexity and nonlinear ‘multi-physics’ interaction in the manufacturing processes. By developing accurate physical and chemical models and analyzing the dominant control mechanisms, this goal can be achieved. Hence it is important to build a ‘model-based product realization’ infrastructure that captures the ‘design-to-fabrication’ processes well.

Current weapon components and systems in the stockpile are the result of many years of design, system engineering, analysis, and testing. In contrast, microsystems represent a relatively new and revolutionary technology. To qualify and certify any microsystem for weapon applications, more work is needed to build confidence and acceptance of this new technology by establishing an efficient model-based qualification infrastructure. This involves developing the following two processes: 1) rapid prototyping with design verification and 2) integrated design with qualification. Rapid prototyping with design verification is to develop a seamless ‘design-to-visualization & analysis’ tool that designers can use to evaluate devices before fabrication. Integrated design with qualification is a strategy that includes design, modeling and simulation, computational tools, and testing required to support design evaluation and performance and reliability analysis.

Figure 1 shows the flow chart of this proposed model-based infrastructure that includes production realization and system analysis. Two manufacturing processes are being considered here: surface micromachining and LIGA. Surface micromachining usually involves a fabrication process to grow structural layer films (polysilicon) and sacrificial layer films (silicon dioxide) on silicon wafers using low pressure chemical vapor deposition and plasma etching. LIGA is a German acronym for lithography, electroforming, and molding. It uses high-energy x-ray

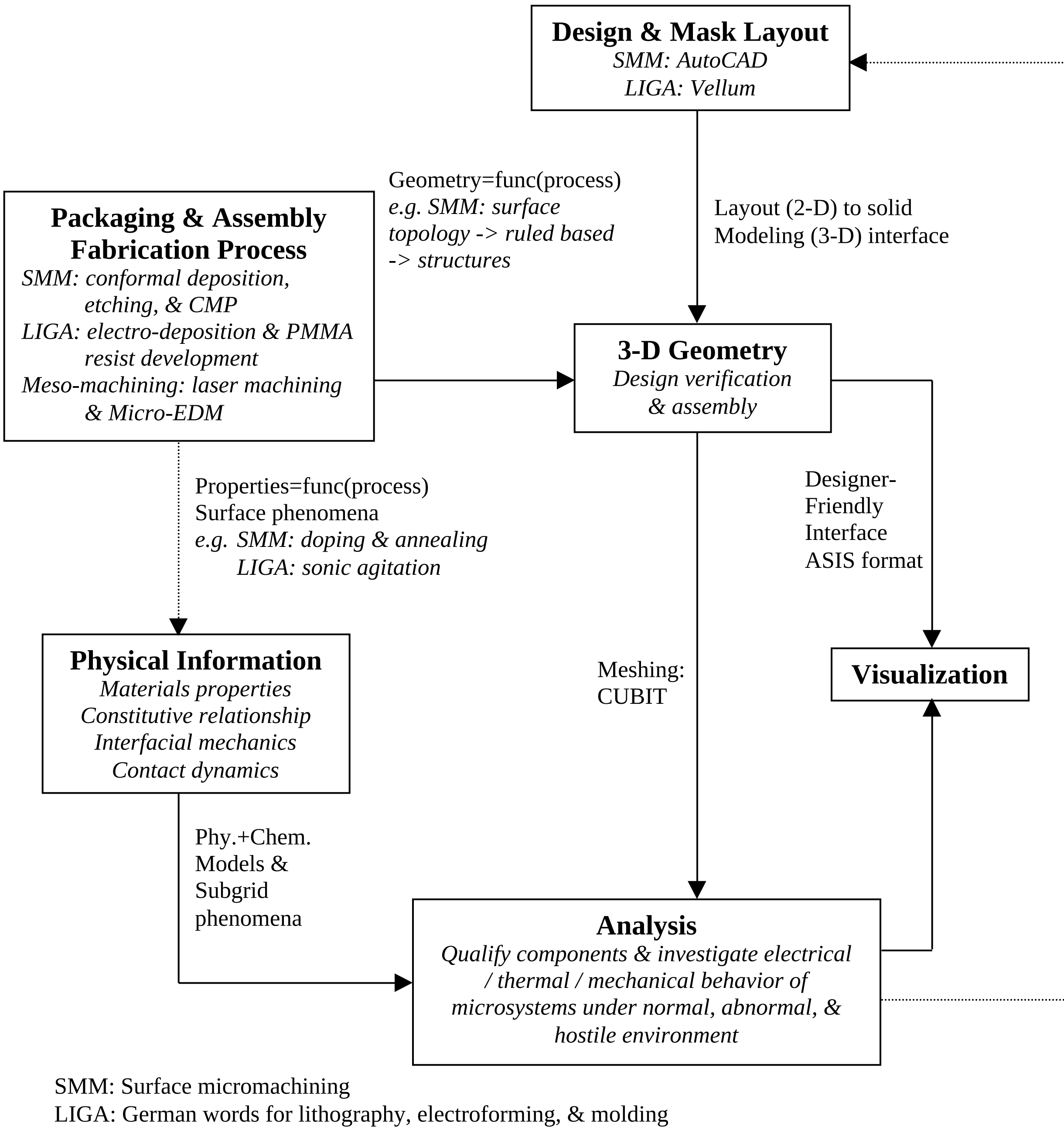

Figure A.1. Flow Chart to Illustrate the Model-Based Infrastructure lithography followed by chemical processing to produce a PMMA mold. This PMMA mold can be used to produce metal parts by electrodeposition or to develop metal molds by electroforming. In general, the LIGA process can produce much higher aspect ratio structures than surface micromachining.

Model-Based Infrastructure

Process Modeling

Both surface micromachining and LIGA involve many processing steps: they are complex, dynamic, and highly nonlinear. These processes are difficult to model because they involve widely disparate length and time scales. Simulation tools that have been developed for the microelectronics industry may be applicable to some of these processes. However the complex fabrication processes being pioneered at Sandia require enhanced modeling beyond the tools that are currently available. Some experimental investigations and model assessments are likely to be required. Thus the initial effort will focus on exploring existing model capabilities for microsystem applications.

The goal of process modeling is to characterize the fabrication process so that better, reliable, and reproducible (consistent) components can be built. Accurate models that capture the essential physics will serve two purposes. First they can be used to to generate the correct 3-D structure and its surface topology developed from the processes. Second they can be used to determine the dominant parameters that need to be optimized in the fabrication processes. An accurate 3-D geometry of the designed device is also needed in the 'model-based' approach to verify the design and qualify the performance of the components and systems before any fabrication and testing.

Surface micromachining

The proposed research addresses two areas: 1) the characteristics of the environment in the reactor chamber and 2) the feature-scale modeling. These areas will be addressed in parallel. It is important to characterize the reactor conditions because the dynamic environment in the chamber controls the outcome of the fabrication process. This approach also allows us to separate the reactor scale from the feature scale. The modeling of the chemical vapor deposition (CVD) and plasma etching processes in reactor scales involves a variety of coupled phenomena (gas phase and surface chemical kinetics, transport, fluid flow). Results of these models will determine the flux distribution on the wafer being processed.

When the flux distribution is defined, a designer can determine the feature shape or the surface topology of the micromachine structures being developed. An important objective is to capture and correct any unintended features resulting from the processing steps (such as stringers) before the design is advanced to the fabrication stage.

LIGA

In LIGA, the primary concerns are large scale voids in the deposited metal and uneven mold filling in the electrodeposition process due to local variations in deposition rate. High frequency sonic agitation can enhance the transport rate to small features and lead to a more uniform deposition rate.

Interest in modeling the electro-chemical processes has grown significantly recently because of the need to better understand electro-chemical phenomena for other critical programs at Sandia, such as the ASCI corrosion program, the μChemLab™ project, fuel cell research, and work on thermal batteries for power supplies. It may be beneficial to develop a generic code to model the common features in electro-chemical processing, then implement specific modules to address the critical needs of the different applications.

Defining the 3-D Structures

Layout-to-Solid Modeling Interface

In surface micromachining, the designs are created as a series of 2-D mask drawings. An accurate 3-D model of the MEMS structures must be created by appropriately combining the 2-D mask geometry with processing information. This 3-D model then serves as the input to a host of other analysis (e.g. FEA, kinematic) and visualization tools. To facilitate the utilization of existing analysis and visualization code, the geometry file resulting from the 3-D model must be able to be converted into the IGES or other appropriate formats.

Meshing

With the structure represented in the IGES format, it can easily be ported into an existing ASCI-supported meshing algorithm such as CUBIT to generate meshes for further analyis, or translated into the ASIS format for visualization.

Analysis for Design Verification and Qualification

To support design evaluation, and performance and reliability analysis, a strategy that includes design, modeling/simulation, computational tools, and testing is vital. In a model-based approach, it is necessary to develop capabilities to address the critical needs in the following areas: 1) electro-mechanics, 2) kinematics, 3) large deflection nonlinear dynamics, and 4) thermal analysis.

Physical Information

Physical information addresses critical knowledge of materials behavior and boundary conditions. As a result of the fabrication processes, the materials properties of the micro-structures may differ from the expected ideal bulk properties. For example, small differences in the doping and annealing processes in surface micromachining may result in a different spring constant for a micro-resonator. Hence it is important to study the following areas: 1) interface /

contact dynamics, 2) critical surface phenomena such as stiction and friction, 3) materials properties, and 4) constitutive relationships

Visualization

The maximum benefit from these integrated models will only be attained *via* an interactive environment by which the designer can both manipulate the rendered 3-D shapes, and manipulate the position/orientation of the viewer. This should be implemented at 2 levels: 1) a large interactive 3-D projection and 2) at the desktop workstation level (high-end PC). Eventually, this interactive environment should include a force-feedback interface by which a user can grasp, deform, and manipulate the virtual mechanical system to analyze the kinematics performance.

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Appendix B

Materials Issues in the Surface Micromachining (SMM) Technology

Understanding & Available Data: None → Insufficient → Limited → Satisfactory
Existing Model: None → Empirical → Semi-empirical → Physically based
Importance to Designers/Systems: Low → Medium → High

Issues	Understanding	Data	Model	Importance
Materials Properties (w/ contact)				
Adhesion (forces required to separate, peel or shear)				
Adhesion energy (smooth/ideal)	Limited	Limited	Semi-empirical	H
Surface chemistry effects	Insufficient	Insufficient	Empirical	M
Force law (VDW, electrostatic, etc.)	Insufficient	Insufficient	Semi-empirical	M
Friction				
Friction force (coefficient)	Insufficient	Insufficient	Empirical	H
Contact pressure	Insufficient	Insufficient	Empirical	H
Single/multiple asperity	Insufficient	Insufficient	Semi-empirical	H
Energy dissipation modes	Insufficient	Limited	Empirical	H
Fluid damping	Limited	Insufficient	Semi-empirical	M
Contact event time scale (velocity)	Limited	Limited	Semi-empirical	M
Microcontact mechanics	Satisfactory	Satisfactory	Physical	H
Topography	Satisfactory	Satisfactory	Physical	H
Coatings / Surface Treatments				
Degradation mechanisms & kinetics	None	None	None	H
Performance characterization	Insufficient	Insufficient	None	H
Robustness (process variability)	Insufficient	Limited	None	H
Wear				
Energy input	Limited	Insufficient	Empirical	M
Mechanisms	Limited	Limited	Empirical	M
Materials Properties (w/o contact)				
Strength of Materials				
Stiffness (Young's modulus & Poisson's ratio)	Limited	Limited	Semi-empirical	H

Issues	Understanding	Data	Model	Importance
Microstructure effects	Insufficient	Insufficient	Empirical	M
Fracture strength (critical flaw size)	Limited	Insufficient	Semi-empirical	H
Fracture toughness	Limited	Insufficient	Semi-empirical	M
Fatigue	Limited	Limited	None	L
Length scale effects on properties	Limited	Insufficient	Semi-empirical	L
Yielding	Limited	Limited	Semi-empirical	L
Coefficient of thermal expansion	Limited	Limited	Semi-empirical	L
Environmental Effects on All the Properties Above (w/ or w/o contact)				
Chemical (humidity, volatile organics, SCC, …)	Insufficient / Limited	Insufficient / Limited	Semi-empirical	H
Thermal	Insufficient	Insufficient	None	M
Radiation	Insufficient	Insufficient	Semi-empirical	M
Process				
Residual stress minimization	Satisfactory	Satisfactory	Semi-empirical / Physical	H
Strain gradient minimization	Satisfactory	Satisfactory	Semi-empirical / Physical	H
CVD control for homogeneous thickness	Satisfactory	Satisfactory	Semi-empirical / Physical	L

Appendix C

Materials Issues in the LIGA Technology

Understanding & Available Data: None → Insufficient → Limited → Satisfactory
Existing Model: None → Empirical → Semi-empirical → Physically based
Importance to Designers/Systems: Low → Medium → High

Issues	Understanding	Data	Model	Importance
Process				
Materials suite	Insufficient	Insufficient	Empirical	H
Process and assembly bonding	Limited	Insufficient	Semi-empirical	H
X-ray photochemistry (e.g. PMMA behavior)	Limited	Insufficient	Semi-empirical	M
Residual stress minimization	Satisfactory	Insufficient	Semi-empirical	H
Deposition	Limited	Limited	Semi-empirical	M
Dimensional Metrology	Satisfactory	Insufficient	None	H
Mechanical and Physical Behavior				
Yield strength and plastic deformation	Limited	Limited	Empirical	H
Elastic response	Limited	Insufficient	Semi-empirical	H
Local microstructural effects	Insufficient	Insufficient	Empirical	M
Magnetic properties	Limited	Limited	Semi-empirical	H
Fracture toughness	Limited	Insufficient	Empirical	M
Fatigue	Limited	Insufficient	Empirical	M
Coefficient of thermal expansion	Satisfactory	Insufficient	Empirical	M
Length scale effects on properties	Limited	Insufficient	Semi-empirical	L
Adhesion / Friction and Wear				
Wear mechanisms and maps	Limited	None	Empirical	H
Topography	Limited	Insufficient	None	H
Single/multiple asperity contact	Insufficient	Insufficient	Semi-empirical	H
Fretting	Insufficient	Insufficient	None	H
Pressure-velocity limits	Limited	None	Semi-empirical	M
Surface/interface energy	Satisfactory	Insufficient	Physical	H
Surface chemistry effects	Limited	Insufficient	Empirical	M
Energy dissipation modes (i.e. temperature rise)	Limited	Limited	None	L
Fluid dynamics at microscale	Limited	Insufficient	Semi-empirical	L

Issues	Understanding	Data	Model	Importance
Environmental and Aging Effects				
Chemical (humidity, volatile organics, SCC, …)	Limited	Insufficient	Empirical	H
Thermal	Limited	Insufficient	Semi-empirical	M
Radiation	Limited	Insufficient	Semi-empirical	L
Coating / Surface Treatments				
Performance characterization	Satisfactory	Insufficient	Empirical	H
Coating materials and processes	Satisfactory	Insufficient	None	M
Reliability	Limited	Limited	Empirical	M

Appendix D

Materials Issues in the Meso-Machining Technology

Understanding & Available Data: None → Insufficient → Limited → Satisfactory
Existing Model: None → Empirical → Semi-empirical → Physically based
Importance to Designers/Systems: Low → Medium → High

Issues	Understanding	Data	Model	Importance
Femto-second Laser Ablation				
Laser-material interaction	Insufficient	Insufficient	Empirical	H
Mass transport for material removal	Limited	Insufficient	None	H
Shock wave created by laser ablation	Limited	Limited	Empirical	M
Damage resulted from shock wave	Insufficient	Insufficient	None	M
Heat transfer & thermal effects	Insufficient	Limited	Empirical	M
Micro-EDM (Electro Discharge Machining) Process				
Interaction between the electrode material, the dielectric material, and the workpiece material				
Wear of the electrode material	Limited	Limited	Semi-empirical	H
Heat transfer	Satisfactory	Satisfactory	Semi-empirical	M
Mass transport	Satisfactory	Satisfactory	Semi-empirical	L
Micro-milling & Micro-turning				
Tool-workpiece cutting interactions	Satisfactory	Limited	Empirical	M

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