Final Report

NSF 2000 WORKSHOP ON MANUFACTURING OF MICRO-ELECTRO-MECHANICAL SYSTEMS

Held at

DoubleTree Club Hotel
Lake Buena Vista, Orlando, Florida

November 7, 2000

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National Science Foundation
Arizona State University

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All opinions expressed in this report are those of the participants and do not necessarily represent the position of the workshop sponsors

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* Attended a portion of the workshop

PREFACE

This report is based on the findings of a workshop sponsored by the National Science Foundation under Grant No. DMI-0002466. The workshop was held at the DoubleTree Club Hotel, Lake Buena Vista, Orlando, Florida on November 7, 2000. The workshop brought together experts from industry, academia, and government in the field of manufacturing of Micro-Electro-Mechanical Systems (MEMS) so that, through synergistic interaction and discussion, existing barriers and opportunities in the field could be identified, research and development priorities could be suggested, and a research roadmap for future research collaboration and investment could be formed. Three critical areas: (a) MEMS fabrication, (b) MEMS applications, and (c) MEMS packaging and reliability, formed the focus of this workshop.

A total of thirty-six delegates from academia, government, and industry, participated in this one-day workshop. Participants were split into three breakout sessions, each of which focused on one critical area. The workshop consisted of presentations of the technical position papers submitted before the workshop by the participants, breakout session discussions on collaboration opportunities and relevant emerging topics in each critical area, and conclusion presentations reached by the participants at the workshop. There was a large degree of unanimity among the suggestions and recommendations, despite the breadth of the subject area and the diversity of backgrounds and interests represented by the participants.

After the meeting the leaders of the three critical areas were responsible for compiling the area recommendations for their respective area. The final draft was composed based on the suggestions and recommendations of the three areas, and sent to all participants for review. The final report has been modified in light of the reviews received. The workshop agenda and a list of contact information of attendees, and submitted position papers are appended to this report. The report does not contain references to the literature. This was a deliberate decision to make the report as generally accessible as possible, without the normal scholarly detail and bibliographic information. However, to provide background information to the readers, three review articles written by three workshop participants respectively are also appended to supplement the information on the historical overview and current research assessment.

In closing, I would like to express my deep gratitude to all the attendees for their time and effort, and for sharing their expertise and insight. Special thanks are due to the members of the Organization Committee, for their efforts in organizing the workshop and preparing the area report. Finally, I would also like to thank NSF Program Director, Dr. Delcie Durham for her encouragement and guidance. I believe that this is a significant event in the field of MEMS manufacturing in this millennium-turning year, the year 2000.

Ampere A. Tseng
Chair, Organizing Committee

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INTRODUCTION

In the last few decades, miniaturization has been an important aspect in the development of technology. Smaller components make the systems faster, more reliable, cheaper and capable of incorporating more complex functions. These miniature parts also tend to be rugged, respond rapidly, use little power, occupy a small volume, and are often much less expensive than conventional macro parts. One of the main goals of miniaturization through microengineering is to be able to integrate the well-developed technology in microelectronic circuitry into the novel technology in micromachined three-dimensional structures, in order to produce completely integrated Micro-Electro-Mechanical Systems (MEMS).

The field of MEMS is extremely broad, including applications such as pressure and acceleration sensors, scanning probe tips for atomic force microscopes, flow sensors, valves, micro motors, and chemical analysis on a chip. Many MEMS are geometrically complicated, electro-mechanically coupled, and inherently three-dimensional. The solution of multi-domain physics problems includes electrical, mechanical, magnetic, thermal, and fluidic effects, which need to be accurately simulated to correctly predict device performance.

In addition, the integrated circuit fabrication techniques widely used today in the manufacturing of MEMS require the modeling of complex material behavior and processing such as oxidation, etching, deposition, and diffusion. Although there have been a number of recent efforts to develop simulation based design tools for MEMS, this emerging field must also draw on numerous disciplines in order to develop the need capability. The strategy in advancing MEMS technologies is to continue the movement toward greater levels of integration. The motivation is to reduce cost, achieve unprecedented levels of system functionality, and to push further the performance to levels enabling vast new application areas.

The primary goal of the workshop was to bring together researchers from a variety of backgrounds to exchange ideas and discuss technical challenges that must be met to advance the technologies and applications of MEMS, as well as to discuss research opportunities for collaboration among experts in MEMS manufacturing. This workshop provided a forum for researchers from academia, government and industry and was comprised of presentations of technical position papers submitted by the delegates, as well as breakout session discussions on collaboration opportunities and the relevant emerging research topics in MEMS.

A total of thirty-six delegates participated in this one-day workshop. Three critical areas: (a) MEMS fabrication, (b) MEMS applications and (c) MEMS packaging and reliability, were selected in this workshop. After the general presentation, the participants were divided into three working group, and each group focused on one focal area. Although the recommendations of each group were reported separately, there was a large degree of consensus among the three working groups despite the breadth of the subject area and the diversity of backgrounds and interests represented by the participants.

The field of MEMS manufacturing is vast, and it is impossible to cover all topics in a one-day workshop. However, every effort was made to include contemporary topics of significant importance to MEMS manufactures, as well as those that would benefit from research done at universities or in collaboration with universities. Moreover, research funding opportunities related to MEMS manufacturing do exist throughout NSF and other government agencies. While programs exist, especially in NSF, in small and disparate modes, optimal impact is only possible if a concerted and coordinated effort is initiated, which embraces new paradigms and combines them with the relevant portions of existing programs. It was one the purpose of this workshop to provide input into this overall process. We hope that this report will serve this purpose.

FOCUS AREAS

Tremendous progress has been made in manufacturing of MEMS. Of particular significance among these areas are: (a) MEMS fabrication, (b) MEMS applications, and (c) MEMS packaging and reliability. In this workshop, these three areas have been specifically examined. The scope and impact for each area are described in this section.

Fabrication

Micro-fabrication technologies have been a driving force for advancement of emerging MEMS and other advanced micro mechanical applications. The bulk and surface micromachining processes have been widely used to make various MEMS devices.

Bulk micromachining has a relatively long history of research and development. It is based on a combination of isotropic and anisotropic etchings of single-crystalline silicon to form micro mechanical structures from the bulk of the silicon wafer. Heated strong alkaline solutions were used to remove silicon material preferentially except the exposed [111] planes. Later, deep reactive-ion etching (DRIE) was developed to enable a greater degree of 2-D design freedom in creating microstructures with high aspect ratios.

Surface micromachining, on the other hand, is based on sequential deposition and etching of thin films on the surface of a carrier substrate. One or more intermediate thin films (the sacrificial layers) are removed in the final steps, leaving the subsequently deposited thin film structures hanging or released from the substrate. These hanging structures form the proof mass and the spring suspensions for accelerometers, or the micro mirrors in digital light processors (DLP).

A unique characteristic of both of these MEMS techniques is their roots in microelectronics technology. The basic lithography, patterning, and batch fabrication approaches and equipments are adopted from the IC industry and customized to create micromechanical devices. At the same time, MEMS fabrication is progressing rapidly beyond the tool sets available in IC manufacturing. Other key techniques include wafer bonding that allows stacking of wafers with microstructures, deep X-ray lithography combined with plating and molding (LIGA) to create high-precision, high-aspect-ratio microstructures, laser micromachining, electro-discharge micromachining (EDM), thin-film or monolayer self assembly, etc. There are also other techniques customized to create microstructures based on materials other than silicon, such as SiC, polymers, ceramics, diamond thin films, metals, alloys, etc.

With the increasing demand in MEMS applications, technical challenges lie in new processes capable of fabricating a variety of materials for MEMS as well as high aspect ratio, complex and inexpensive microstructures. However, the mechanical interfacing of silicon-based systems to the non-silicon world has been a problem. Broader micro fabrication technologies need to be explored and established to achieve the goal of making complex and reliable MEMS devices inexpensively.

Applications

The maturity of batch fabrication in IC foundries makes it possible to produce MEMS in large volumes at an extremely low cost. Because of these advantages, surface micromachining is being aggressively pursued and applied by many in the MEMS community. The complexity of devices that may be created using surface micromachining is governed by the number of mechanical layers available in the given fabrication process. Adding multiple mechanical levels not only enables the creation of linkages to connect actuators to mechanisms but also opens up an entirely new range of design possibilities that is staggering in scope.

One of the principal commercial MEMS products is inertial sensor. These accelerometers find their primary application as airbag-deployment sensors in automobiles, but are also being used as tilt or shock sensors. The application of these types of accelerometers to inertial measure units is limited by the need to manually align and assemble them into three-axis systems, the resulting alignment tolerances, their lack of on-chip A/D conversion circuitry, and their lower limit of sensitivity. A long-term goal of a micromachined micro-navigation system requires both 3-axis accelerometers and gyroscopes. Therefore, advances in manufacturing techniques are needed for micromachined systems-on-a-chip enable sensor systems with greatly increased degrees of complexity to be fabricated on a single chip.

Micromechanical actuators have not seen the widespread industrial use that micromechanical sensors have achieved. Two principal stumbling blocks to their widespread application have been low torque and difficulty in coupling tools to actuators. There is a critical need to develop multiple level micromachining processes, which enable intricate coupling mechanisms that link MEMS actuators to various tools. Several devices such as microengines, microtransmissions, microlocks, and micromirrors have been built based on this technique. The new challenge is to innovatively combine those devices to yield intricate mechanical systems.

Recently, a great deal of interest has been devoted to manufacturing processes that allow the integration of MEMS devices with driving, controlling, and signal processing electronics. This integration promises to improve the performance of micromechanical devices as well as to reduce the cost of manufacturing, packaging, and instrumenting these devices by combining the micromechanical devices with an electronic sub-system in the same manufacturing process.

Packaging and Reliability

MEMS packaging can be defined as all the activities or concerns after device fabrication. They include post-processing release, package/substrate fabrication, assembly, testing and reliability. In each packaging step, there are design and manufacturing issues. Reliability is in fact one of the performance measures that are strongly affected by the package as well as the device. However, it is usually considered as one of the packaging activities/concerns because packaging rather than fabrication manufacturers usually conduct environmental protection process, burn-in and accelerated tests for reliable MEMS products.

Though the electronics manufacturing industry has a robust and viable infrastructure, direct application of electronics packaging techniques to most MEMS parts is not feasible because of the complexities of their operational structure and domain. For example, packaging should allow some moving parts to interact with other components through optical, electrical, thermal, mechanical or chemical interfaces. As a result, many MEMS packaging problems are new to most of electronic packaging engineers. Here are a few examples:

- Vacuum packaging might be needed when viscous damping is important.
- Die-attachment might affect the pressure measured through thermal stresses.
- Thermal strains might affect the performance of piezoresistive or membrane devices.
- Moisture could cause stiction problems.
- There are no effective thermal paths for thin micro-mirrors for heat transfer.
- There are no accelerated tests since most of failure mechanisms for the moving parts are unknown.

Packaging also has been identified as one of the major technical barriers that might hamper the growth of MEMS applications. It strongly affects a MEMS device's performance and reliability through mechanical, thermal, electrical, or chemical interactions. Packaging costs can be more than 50% of a component's total cost; therefore, unique challenges in MEMS packaging need to be addressed. The full range of MEMS reliability techniques also need to be developed to cover the topics from the basics of failure analysis on MEMS devices, through mechanisms of failure and basic surface science to packaging issues.

FABRICATION GROUP RECOMMENDATIONS

It is the consensus opinion of this group that MEMS fabrication technologies, in certain selected areas, have matured beyond the research and development stage and have enabled several high-volume products. Currently, the largest market segments for the MEMS industry include silicon-based pressure sensors, air-bag crash sensors, print heads for ink-jet printers, and digital light processors (DLP) for video projectors. The fabrication technologies that enable these high-volume products fall under two broad categories: bulk micromachining (e.g., pressure sensors and ink-jet print heads) and surface micromachining (e.g., air-bag accelerometers and DLP).

Challenges

It is the consensus of this group that there remain significant challenges in MEMS fabrications that are worth investigating. There is little dispute that MEMS fabrication research requires a multi-disciplined approach. In contrast to the IC industry, there are virtually no standardized MEMS fabrication techniques equivalent to the CMOS technology that will satisfy a majority of MEMS device fabrication needs. The materials used in MEMS fabrication are also far more varied than in electronics. Furthermore, compared with the IC industry, the volumes in MEMS are inherently lower due to the specialized nature of the specific devices. Finally, it is also obvious to this group that MEMS fabrication is coupled with the specific application as well as packaging and reliability, which are the subject matters of the other two groups.

Due to the vast diversity in MEMS fabrication methods and the intended applications, the task to establish prioritized lists for research investment and technology roadmaps are more complicated than those for the microelectronics industries. This group engaged in in-depth discussions on this issue. Several findings are outlined in this report.

Research Topics

There are several proposed research topics in MEMS fabrication:

LIGA and Ultra-Deep LIGA

The goals are to establish a LIGA process that is manufacturable and to enable precision microstructures as thick as several mm. Research issues include

- Wet developing process
- Thermal stress control
- Numerical simulation of wet processes
- Materials issues
- Micro-embossing technologies
- Science of plating high-strength alloys
- Extending and including LIGA to larger-dimension objects.

The potential benefits include

- Low-cost manufacturing of molding microstructures with wide choices of structural materials
- Excellent heat transfer characteristics in the final metal or alloy devices
- Molds for polymer and plastic parts

Further Miniaturization and Nanofabrication

The goal is to establish processes to create sub-micron-scale devices. Research issues include

- Internal dissipation and materials characteristics
- Surface science of nanostructures
- Transduction mechanisms
- Integration techniques with micromechanical devices and electronics,
- Ever-higher aspect ratios
- Dimensional uniformity and repeatability
- Combining both small (microns and sub-microns) and large (> cm) dimensions in the same process flow
- Speed and throughput of nanofabrication processes
- Sciences of ultra thin-film coatings
- Laser/FIB/FEB maskless fabrication

- CAE/CAD/CAM tools for process flows and atomistic designs

The potential benefits include

- Higher operating frequencies
- Potentially greater durability
- Ultra-sensitive force and/or mass detection
- Enabling novel toolbox for nanostructural studies of materials, etc.

Polymers and Other New Materials

The goal is to establish processes that incorporate new materials beyond silicon, such as "active" materials, optical coatings, polymers, plastic, biodegradable materials, etc. Research issues include

- Process compatibility with existing MEMS fabrication techniques
- Diversity in processing techniques and properties of polymers
- Scaling polymer processes to MEMS level
- Multi-functions and multi-materials systems
- Processing of quartz and glass
- Optical properties of transparent and translucent materials
- Integration with electronics and mechanics

The potential benefits include

- Better performance and better suitability for specific applications such as biomedical, RF MEMS, harsh-environment applications
- Polymers are suitable for low-to-medium-precision device applications
- New functionality
- Low-cost production at all production volumes
- Disposable products
- Biocompatible devices
- Self-packaged polymer devices
- True 3-D shapes
- Leveraging the existing vast infrastructure of the polymer industry

Manufacturing Sciences and manufacturing infrastructures

The goals are to establish the technology to ensure manufacturability and to establish a resource for flexible manufacturing to support different process sequences while maintaining high quality, reproducibility, and relative low cost. The specific research topics include

- The science and physics of surface properties of materials used in MEMS fabrication
- The study of bulk properties of materials used in MEMS fabrication
- Effective and coordinated uses of standard process control monitors
- Process and quality controls methodologies
- The physics of contamination causes and effects
- Low-temperature fabrication processes
- Non-silicon fabrication technologies
- The use of computer modeling for prediction of process outcomes
- The development of software technology for manufacturing databases
- Process modularization
- Undergraduate trainings in generic Statistical Process Control (SPC) and Design of Experiments (DE)

The benefits include

- Understanding and/or lowering the substantial entry barriers into MEMS
- Efficient and cost-effective prototyping of research designs
- Stable manufacturing process for small to large volume productions
- Short product development cycles
- Increased accessibility to fabrication infrastructures
- Enhance MEMS fabrication predictability, repeatability, and producibility

Analyses of Research Topics

The group analyzed the proposed research topics in relative terms of technology push vs. application pull as well as near term (a few years) vs. long term (10 years and beyond). The results are summarized in Table I. It should be noted that the listed research topics all require variable degrees of design tools and CAD abstraction technologies.

Table 1. Comparison of the four research topics in MEMS fabrication in relative terms*

Technology Push (T/t) vs. Application Pull (A/a)	Near Term (N/n) vs. Long Term (L/l)	Research Topics
t A	Nl	MEMS manufacturing sciences and infrastructure
T A	n l	Polymer and other MEMS materials
T a	L	Nano fabrication
	n	Thin-film coating
T a	L	LIGA / LIGA-like processes
	N	Molding plastics
	L	Molding of other materials

* "T" represents strong technology push and "t" weak technology push, while "A" represents strong application pull and "a", weak application pull. Similarly for "N", "n", "L", and "l" for near term vs. long term.

One clear observation that stands out from the analyses is that the topic of MEMS manufacturing sciences and infrastructure should be at the top of research priorities because there exists a critical near-term need that is based on strong application pull. This research topic has the potential of maximum impact on the advancement of the MEMS field and the highest payoff on research investment. However, due to some inevitable issues in sensitivity and competitiveness in the commercial arena, the government needs to play a crucial role in facilitating pre-competitive collaboration in the pursuit of this topic to eliminate wasteful duplication of research efforts and to lower the entry barriers for general MEMS developers.

APPLICATIONS GROUP RECOMMENDATIONS

Micro-electro-mechanical systems (MEMS) is an emerging technology that enables the mass production of highly integrated systems. The vision of MEMS systems is the ability to sense, think, act and communicate through the integration of electronics, mechanical actuators and sensors. MEMS have been under development since the late 1970's on the possibility of silicon as a mechanical material. The bulk of the MEMS research in the 1980's was focusing on fabrication technologies and demonstration of a few rudimentary actuation devices such as the electrostatic comb drive.

Challenges

The late 1980's and early 1990's saw the development of early MEMS products such as pressure sensors, accelerometers (ex. ADXL50 – Analog Devices), and the Digital Micromirror Device (DMD - developed by Texas Instruments). The major drivers for MEMS devices include: cost, size/weight, performance, reliability and new "enabled" capabilities. MEMS devices use a variety of fabrication processes (e.g. Bulk micromachining, surface micromachining, LIGA, meso-scale machining). Thus the major challenge for success of MEMS technology is the non-homogeneous nature of the fabrication technologies and applications required by the MEMS marketplace. The MEMS infrastructure elements that enable application designs are also lacking. The MEMS infrastructure elements that need to be developed are: 1) Design Layout tools, 2) Design Visualization, Auto-Realization, and Design Optimization

Due to the small size of MEMS devices, features are frequently defined via photolithography processes, which require two-dimensional masks be designed to realize three-dimensional devices. The challenge to the design engineer in this environment is the visualization of the resulting device and checking that the design meets the fabrication process design rules. The existing microelectronic infrastructure is totally inadequate to meet these needs. A fundamental understanding of the physics at the micro-scale is still lacking. Development in the areas of experimental validation techniques and analytical modeling at the micro-scale will assist the design engineer to ensure a successful design.

MEMS applications range from the existing commercially available pressure and inertial sensors, to the current development of optical and RF MEMS applications, to the research of chemical/biological/fluidic MEMS devices. The research and development of MEMS power sources is also on the distant horizon.

Research Topics

The application-working group chose to look at the research areas for MEMS applications in two categories: 1) Enabling MEMS Infrastructure and 2) Applications.

Table 2 summarizes the enabling MEMS infrastructure that needs to be developed to facilitate MEMS application designs. There is also a rating of where in the spectrum of research through application any particular aspect resides. Computer aided design tools for MEMS layout and visualization is now entering the marketplace with most of the work being in the application arena. Where as the auto realization of a MEMS design, which is expressed frequently as a two-dimensional lithography mask layout, from a three-dimensional (solid model) representation of the MEMS device concept is not available at the current time and this will be difficult to achieve. Design optimization of MEMS devices is just now being attempted. MEMS devices are fabricated in processes that are highly variable; therefore, the optimization of systems with stochastic design variables is an example of a relevant problem.

The most enabling piece of MEMS infrastructure is the understanding of physics at the micro-scale. The design of MEMS devices, that can achieve the precision required, need analytical modeling tools which capture the relevant physics of the device as well as the ability to experimentally validate the design and/or the analytical model. The relevant modeling and experimental validation tools do not currently exist and significant research is necessary to push the bounds of knowledge forward.

Table 3 shows a variety of MEMS applications that range from existing products to devices that are in the research stages and have not yet been realized. It is in the development of MEMS devices for applications that lay at the intersection of fabrication, design, and packaging technology. The application arena will frequently drive a technology such as MEMS in its priorities. Table 3 is an attempt to categorize, in a broad sense, the applications that either exists or in the research/conceptual stages. The applications at the research/concept stage require development of design expertise in modeling and experimental validation. But these applications will also push the limits of fabrication technology and packaging technology in order to achieve the full capabilities of MEMS for use in these fields.

Table 2. Enabling MEMS Infrastructure

Computer Aided Design	**Research-Development-Application (5 - - - - - - - - - - - - - - - - 1)**
Design Realization Tools	1
Design Visualization	1
Auto Realization	3
Design Optimization	5
Analytical Modeling at the Micro Scale	
Multi-Domain Modeling	5
Physics at Micro Scale	5
Macro Modeling (Systems)	5
Experimental Validation at the Micro Scale	
Material Properties	5
Metrology of Devices	5
Material Interactions	5
Operational Characterization	5

Table 3. MEMS Applications

Application	**Example**	**Research-Development-Application (5 - - - - - - - - - - - - - - - - 1)**
Pressure		1
Inertial Sensor	*Accelerometer, Gyroscope*	2
Actuators	Electrostatic, Magnetic, Piezo	3.5
Optical	Switches, Optical Bench on a chip	3
RF (radio frequency)	*Filter, Switches, Antenna*	4
Chemical Sensors	*Sensors, Lab-on-a-chip*	4
Biological and Fluidic	*Fluid components, Bio-chip*	5
Power Devices	Micro-reactors, fuel cell, energy storage devices	5

PACKAGING AND RELIABILITY GROUP RECOMMENDATIONS

Packaging and reliability challenge is a well-known potential showstopper to the growth of MEMS applications. Packaging cost is about 50 to 90% of the total cost, and reliability is always a top killer issue for every MEMS product. The working group has identified and discussed four challenges that demand in-depth, scientific research studies: functional interfaces, reliability, modeling and integration. These challenges will be discussed with a few examples of basic studies needed.

Challenges and Research Topics

Packaging (including reliability) has been and continues to be a major challenge. Packaging cost is about 50 to 90% of the total cost of the MEMS product. At the present time, custom packaging solutions and reliability qualification processes have been developed for specific products. Such a solution procedure has a potential of stalling the rapid growth of MEMS applications. MEMS packaging (including reliability) is a well-known potential "show stopper." Four challenges to packaging and reliability have been identified: functional interfaces, reliability, modeling and integration. They will be discussed as follows.

Functional Interfaces

Figure 1 illustrates a typical MEMS package with different functions. The package provides functional interfaces between the MEMS device and the environment. The input interfaces are controlled by the desired electrical inputs and affected by tolerated and rejected environmental influences. The output interfaces are accompanied by desired electrical outputs and some byproducts. In addition, test inputs and outputs are critical package functions to qualify a product.

The functional interfaces are directly related to the applications. Unfortunately (or fortunately), MEMS has a large number of diverse applications: microfluidics related to bio-medical applications, data storage, microsurgical instruments, RF communication, optical communication and interconnects, energy storage, display, etc. As a result, different functional interfaces needed are: optical, RF, thermal (radiation, conduction or convection), fluids (liquids or gases), mechanical (body or surface loadings) and others (e.g. radiation, magnetic, etc.).

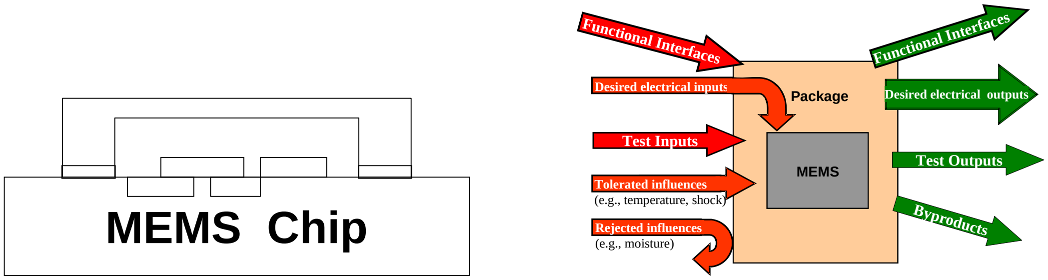

Figure 1: A typical MEMS package and its functions

Each functional interface has its challenging requirements. Here is an example list of major requirements in a package for optical MEMS :

- Reduction in packaging costs: materials and assembly (automated)
- Reduction in package size
- Improvements in Low Temperature Co-fired Ceramics (LTCC) process capabilities
- Hermetic packaging
- Quasi-hermetic packaging
- Particle control
- Automated inspection equipment /test equipment
- Stiction control
- Die attach capability

Similar or very different requirements exist for every functional interface mentioned above. As a result, it is impossible to develop a "standard" package to serve all the MEMS functional interfaces. In fact, using microelectronic packaging as a reference, it is clearly very challenging to develop a "standard" package to serve even one functional interface. Nevertheless, it is the opportunity for packaging researchers to study and develop packages that may serve as many functional interfaces as possible.

Here is a list of basic studies proposed by the working group:

- Modification of standard microelectronics packages to provide additional optical, RF, thermal (radiation, conduction or convection), fluids (liquids or gases), mechanical (body or surface loadings) or others (e.g., radiation, magnetic, etc.) functional interface.
- Develop a package to serve a set of functional interfaces. For example, the functional interfaces can be grouped as solid or fluid interfaces or as physical or chemical interfaces. Sometimes, we may develop a package to serve one group of functional interfaces.
- Selective membranes for chemical- or bio-MEMS.
- Hermetic sealing using gaskets, o-rings or low-temperatures brazing or welding methods.
- Non-hermetic sealing using adhesives, gaskets, o-rings, etc.

It should be noted that the list is served as examples, which can be used to simulate novel proposals. The list is not comprehensive and should not be used as the guidelines.

Reliability

Stiction, fracture and fatigue, mechanical wear with respect to frequency and humidity, and shock and vibration effects are the major causes of MEMS failures. For example, a potential reliability problem for Texas Instrument's digital mirrors is that the mirror might get stuck by particle contamination, surface residue and capillary condensation. Another example is Sandia Labs' driver gear that might suffer a pinhole wear problem after 10^5 cycles.

There are two approaches to develop reliable MEMS. One is the reliability assurance by testing existing structures and the other is by processes/materials development. For the reliability test, the problem is three-fold: 1) the new failure mechanisms are poorly understood and modeled, 2) methods (tests) for accelerating these new failure mechanisms are not defined or understood, and 3) for a given life cycle environment we have to be able to figure out which failure mechanisms are relevant (and which are not) in order to design an accelerated test that actually accelerates relevant mechanisms (versus accelerating mechanisms that are not relevant). In many cases, different failure modes may demand conflicting requirements. For example, humidity may not be desirable since it might cause stiction problems; however, a certain humidity level is good to reduce the wear.

For the processes/materials development, non-hermetic environment and the control of friction and stiction are critical considerations. For example, getters are important materials being used to control the low temperature moisture, high temperature moisture, and micro-particles. Another example is the development of nano-technologies to coat and protect the device for reliable MEMS.

Here is a list of basic studies proposed by the working group:

- Moisture control in non-hermetic packages: 1) “metal” gasket/sealing with compliance, 2) active control of atmosphere, and 3) design and selection of getters
- Stiction: 1) low surface energy films, 2) quantitative understanding of stiction, geometric and surface roughness effects, effects of surface microstructure and chemistry, nano-scale coating, and accelerated testing for stiction
- Accelerated testing (ALT): 1) identification, understanding and modeling of failure mechanisms: stiction, wear… 2) damage accumulation of devices, and 3) material properties and fatigue behavior in micro-scale structured materials
- Qualification: 1) application specific methodology for accelerated qualification (85/85 good test?), 2) MEMS specific testing methodology and equipment, and 3) burn-in pressure w.r.t. functional interfaces

Again, the list is not comprehensive and it is served as examples to simulate novel proposals.

Modeling

Package is usually an integral part of the device. Both device and package have to be designed at the same time. In order to have a one-pass design, physical and semi-empirical models have to be developed. With the diverse applications, a MEMS CAD tool might need to cover every engineering discipline: electrical, thermal, mechanical, optical, electromagnetic wave, and chemical. How to integrate all the existing tools with innovative interface solutions will be challenging. In addition, how to design MEMS for reliability will be as important as the aforementioned tests and new processes/materials.

The state-of-the-art CAD tools are being developed to conduct integrated analysis with the consideration of electrical, thermal, mechanical, optical, and electromagnetic wave performance. Such an integrated analysis is very challenging when the device and the package become complicated. Furthermore, the growth of fluidic- and bio-MEMS demand efficient modeling to cover fluid and bio-chemical phenomena. Such modeling needs many basic studies.

Here is a list of basic studies proposed by the working group:

- Materials properties: 1) temperature and strain rate dependent, and 2) aging
- Experimental techniques: in-situ determination of properties
- Failure modes and mechanisms: physics of failures, e.g. optical misalignment or permanent aging
- Integration of different models including those for bio-medical devices and functions
- Stiction modeling
- CAD tools methodology and integration
- Multi-component and multi-phase modeling for environmental control with or without getters
- Micro-scale transport phenomena

Integration

As indicated in the Functional Interface challenge, MEMS packaging and reliability is strongly related to applications. In addition, packaging and reliability is also strongly related the device fabrication. For every MEMS product, there is always an integration issue needs to be considered: where and how to integrate the fabrication and the packaging processes? Such an integration consideration also provides us an opportunity to create new concepts or technologies for low-cost, high-performance MEMS.

For example, wafer-level packaging can be completed in the same fabrication facility; it may eliminate a packaging step. Such a packaging approach would result in low-cost and very compact MEMS and is the main development target for most of MEMS packages being manufactured today. On the other hand, packaging technologies can be used to fabricate

MEMS devices; it may again eliminate a packaging step since the fabrication is the packaging step. Flexible circuit board technologies have been used to develop paper movers and RF MEMS switches. Co-fired ceramics technologies are very popular to develop bio-MEMS and high-temperature MEMS.

In addition, fabrication and packaging technologies can be integrated to form new MESM. For example, solder technologies have been developed to self-assemble MEMS. The combination of the planar fabrication and the solder self-alignment enables us to develop three-dimensional, complex MEMS without demanding complicated fabrication processes.

Here is a list of basic studies proposed by the committee:

- Incompatible fabrication, packaging and testing: 1) PCB for MEMS fabrication, 2) ceramics for MEMS fabrication, 3) wafer-level packaging including release, lubrication, test and seal, and 4) novel dicing
- Interconnects: 3-D stacking of MEMS devices

Other Studies

The above challenges cannot cover all the issues, and the proposed list of studies cannot reflect the exciting opportunities for researchers interested in packaging and reliability. Therefore, we have generated additional list of proposed studies:

- Restricted motion packaging: A major feature of MEMS is that it moves. As a result, it may be necessary to use package to guide the MEMS movement along a particular direction.
- Nano packaging: Nano-devices are being demonstrated for many new applications. How can we package and interconnect them?
- Self-assembly using DNA, surface tension, eletromagenetics: In the scales of μm, there are many other self-assembly mechanisms in addition to soldering. Which ones should be used and how?
- Givers (lubricants): Getters are to get the undesirable materials out of the inside environment in a package. But, sometimes, we may want some desirable materials inside. Can we produce a giver to release lubricant at a desirable level?

- Automatic test pattern generation during device design: Testing is a major cost issue. It is important to design MEMS with testing as one of the major design considerations. It is possible the test inputs/outputs need to be generated while designing.
- BIST for MEMS : Test pattern generation might not be cost-effective when the test becomes a complicated issue. Built-in self-test (BIST) is used widely to solve this problem for VLSI integrated circuits and sensors. It is expected to play a key role for actuators. Can we have a MEMS design with BIST?

From this list, it is clear that there are many packaging and reliability issues outside the four challenges mentioned above. The area of packaging and reliability is a potential showstopper to the growth of MEMS applications. On the other hand, it also provides us with an opportunity to make an impact. The committee does expect a significant growth of research studies focusing on MEMS packaging and reliability. Such a growth will be essential to keep US industry competitive.

SUMMARY

In this workshop, we concluded that the best strategy is to focus on MEMS manufacturing sciences and infrastructure in the investigation of the coupling among the “Fabrication,” “Application,” and “Packaging and Reliability” groups. In summary, the least favorable approach is to pick some application areas as vehicles to pursue manufacturing sciences and packaging and reliability research. It necessarily limits the scope and thus the values of the scientific investigation and confines the applicability to a few MEMS products. Instead, the following two concluding statements represent the recommendations to NSF that will most strategically advance the MEMS field with the best use of government resources:

- Identify several key research topics in MEMS fabrications with the broadest applications and pursue the associated manufacturing sciences and related packaging and reliability issues.
- Pick the most critical reliability and packaging issues in MEMS and pursue the associated manufacturing sciences and potential applications.

In both approaches, the key emphasis is on scientific investigation with potential applications as the justification. The specific science research topics are listed in this report above. Of particular interest and importance are those listed under MEMS manufacturing sciences and infrastructure.

Finally, MEMS has been and continues to be the major challenge in every system integrating optical, microwave, digital and MEMS components. It is time for NSF and other funding agencies to establish a systematical program to promote MEMS manufacturing research. The program will develop long-term systematical research activities to be carried out by centers, multiple-investigators and single-investigators. More importantly, this program will define not only the top priority topics to be addressed but also on how the collaborations are to be coordinated.

Here is a list of action items recommended:

- Hold workshops on: 1) education, performance, test and modeling, 2) infrastructure development, and 3) supply chains
- Develop national centers on MEMS manufacturing with an emphasis on Fabrication, applications, and packaging and reliability.
- Develop an NSF home program for manufacturing of micro- and nano-systems
- Develop a foundry service for multi-functional microsystems.

APPENDIX A: WORKSHOP AGENDA

NSF 2000 Workshop on Manufacturing of Micro-Electro-Mechanical Systems
DoubleTree Club Hotel, Lake Buena Vista, Orlando, Florida
November 6-7, 2000

Monday, November 6, 2000 (Tropical Room Lounge)

18:00-20:00 Workshop registration and welcome reception

Tuesday, November 7, 2000

Morning Session (Tropical Room)
7:00-8:00 Continental breakfast
8:00-8:15 Welcome and Introduction (Professor Ampere A. Tseng)
8:15-8:30 Opportunities for collaboration: The NSF Perspective (Dr. Delcie R. Durham)

Overview Session (Tropical Room)
8:30-9:00 Overview in MEMS Fabrication (Dr. William C. Tang)
9:00-9:30 Overview in MEMS Applications (Dr. James Allen)
9:30-10:00 Overview in MEMS Packaging and Reliability (Professor Yung-Cheng Lee)

10:00-10:30 Coffee break (Tropical Room)

Breakout Session (Breakout Room)
10:30-12:00 Group I: MEMS Fabrication (Dr. William C. Tang)
Group II: MEMS Applications (Dr. James Allen)
Group III: MEMS Packaging and Reliability (Professor Yung-Cheng Lee)

12:00-13:00 Lunch (Tropical Room)

Breakout Session (Breakout Room)
13:00-15:00 Group I: MEMS Fabrication (Dr. William C. Tang)
Group II: MEMS Applications (Dr. James Allen)
Group III: MEMS Packaging and Reliability (Professor Yung-Cheng Lee)

15:00-15:30 Coffee break (Tropical Room)

Joint Session (Tropical Room)
15:30-16:30 Group Presentation and Joint Discussions (Drs Tang, Allen & Lee)
16:30-17:30 Joint Recommendation (Drs Tang, Allen & Lee)
17:30-18:30 Conclusion and Summary (Drs Tseng/Tang)

18:30 Adjourn or Dinner

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