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Hidden Challenges to MEMS Commercialization: Design Realization and Reliability Assurance

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Abstract

The successful commercialization of MicroElectro-Mechanical Systems (MEMS) is an essential prerequisite for their implementation in many critical government applications. Several unique challenges must be overcome to achieve this widespread commercialization. Challenges associated with design realization and reliability assurance are discussed, along with approaches taken by Sandia to successfully overcome these challenges.

Introduction

MicroElectroMechanical Systems (MEMS) are expected to revolutionize the world. [1,2] They already occur in products as widespread as automobiles, projection systems, and printers. [3-5] MEMS are being developed that will further enhance the safety of the world in multiple and significant ways. They will enable not only numerous new types of automobile safety systems, for example, but will also be used to enhance the safety of future weapon and defense systems. The successful commercialization of MEMS is of great importance to the developers of government safety systems; commercialization results in an incredible amount of essential information pertaining to the performance, reliability, and qualification of MEMS.

The success of pioneering government and commercial applications of MEMS is not occurring without significant development costs. These costs are incurred because of the fact that MEMS technology has not yet matured to the point where there exists a comprehensive supporting infrastructure. In contrast, the Integrated Circuit industry has matured over the past 30 years to the point where it is benefiting from a trillion dollar infrastructure investment. The rapid and successful commercialization of MEMS for a broader range of products requires careful decisions to be made regarding how to most effectively create the needed infrastructure. Just as with integrated circuits, this commerically-driven infrastructure development will greatly facilitate the incorporation of MEMS into essential government systems. The required infrastructure spans the range from design realization to fabrication to reliability assurance.

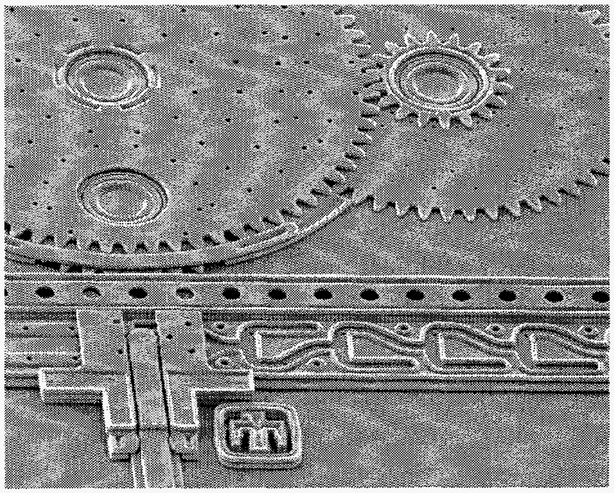

Figure 1. Portion of a microscopic mechanical locking system. Gear teeth are the size of a red blood cell (~7 microns across). This device is batch fabricated, with no piece part assembly, resulting in very low production costs.

It is worthwhile to briefly consider the attributes of MEMS technologies that might drive commercialization of MEMS-based products. While a very useful attribute of MEMS for government applications is their small size, the primary driver for commercial applications is their extremely low cost. For example, polysilicon surface micromachining, [6,7] a method for creating MEMS directly on the surface of a silicon wafer, enables the batch fabrication of MEMS just like integrated circuits (Fig. 1). This batch fabrication approach can result in complete systems at an incredibly low cost. Low cost results in high volume and tremendous economic opportunity for both MEMS manufacturers as well as those developing infrastructure products.

We now consider two aspects of infrastructure development, design realization and reliability assurance, that are needed for low cost, batch fabricated, surface micromachined MEMS. The technical accomplishments and leadership Sandia is providing in these areas is also discussed.

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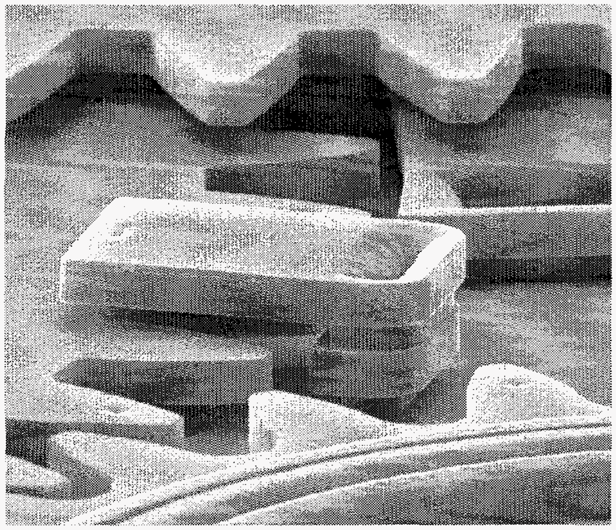

Figure 2. Complex 3-dimensional structures result from the series of 2-dimensional drawings specifying the fabrication mask layers.

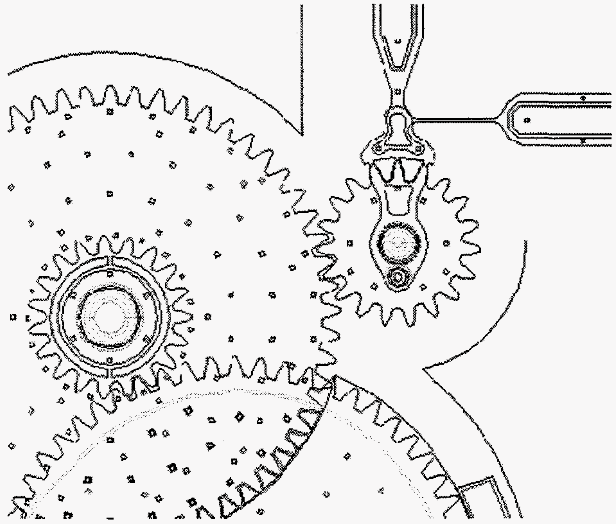

Figure 3. Creating complex device shapes, such as the involute gear teeth in this transmission layout, are not feasible using conventional IC layout tools.

Design Realization

Widespread access to MEMS technology has generally been very limited, in part because of the unique challenges associated with design. Surface micromachined devices consist of 3-dimensional structures created using the same fabrication tools and processes as those used to make conventional integrated circuits. These processes involve thin film deposition, photo-lithographic patterning, etching, etc. The incredible challenge lies in properly specifying the series of 2-dimensional drawings used for the photolithography masks that result in the desired 3-dimensional structures (Fig. 2). Several issues are involved here.

Geometry

Traditional IC layout tools typically support geometries that consist of lines, rectangles, and simple closed polygons. In contrast, MEMS designs are not limited to these simple geometries. The complex shapes associated with advanced MEMS (see Figure 3) require much more sophisticated tools. Sandia National Laboratories is currently creating its mechanical design infrastructure based on the popular commercial design tool AutoCAD. Files that customize AutoCAD in ways that greatly facilitate the layout process for Sandia's 4-level polysilicon technology have been created and are distributed on CD. Several other companies are following Sandia's leadership in this area; they are currently in the process of adding complex geometry capability to their IC layout tools in order to support a broader range of MEMS design needs.

Design Rules

Design rules help insulate the designer from having to understand the subtle details of fabrication processes. Following design rules when creating the 2-d mask drawings helps to ensure that properly fabricated devices will result. The specification of the design rules for MEMS technologies is a challenge because of the complex topographies that can be produced by the technology. The arbitrary shapes used by creative MEMS designers also pose significant challenges regarding the implementation of computer automated design rule checking (DRC). Sandia is providing leadership to the industry by distributing on CD a complete set of design rules for its 4-level surface micromachining technology, as well as providing an automated remote DRC capability. This is the first DRC capability that has been developed for a 4-layer MEMS technology. It is being used by universities, companies, and government agencies.

Standard Components Libraries

The rapid creation of new IC designs relies heavily on the existence of standard cells, or standard components libraries, from which the designer can copy and paste layouts. In a similar way, comprehensive libraries of standard MEMS components are needed to reduce the time to create new designs. Sandia has established

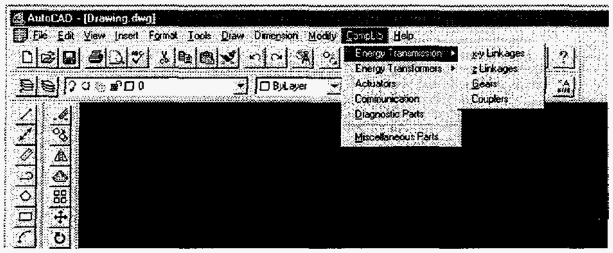

Figure 4. Standard components for Sandia's 4-level MEMS technology are accessible from menus in AutoCAD.

collaborations with universities and government agencies that is resulting in designs that will augment their own expanding standard components library. Sandia's existing standard components library is distributed on CD, and is directly accessible to the designer from pull-down menus in AutoCAD (Fig. 4).

Visualization for Design

While in the process of creating the layout drawings, it is a challenge for even the most experienced MEMS designer to synthesize in his or her mind the 3-d shapes resulting from those drawings. The ability to design by anyone other than highly trained MEMS designers requires visualization tools that are fast, easily accessible by the designer during the layout process, and whose user interface is relevant. Sandia has developed a visualization tool that automatically combines the 2-d AutoCAD drawings with processing specifications to create a 3-d image navigable by the designer, all without leaving the PC design workstation (Fig. 5).

Finite Element Analysis, Kinematics, and System Modeling

Numerous challenges remain in the areas of finite element analysis (FEA), kinematic modeling, and overall system modeling. Traditionally, FEA is performed using 3-d drawings that are created separately from the 2-d drawings used to physically create the device. Besides the fact that the shape being modeled is not likely to be the same as the actual shape of the real physical device, separate origins for the drawings can result in the introduction of inadvertent errors. It is also a costly use of time. The desired goal is to produce meshable solids for FEA directly from accurate 3-d models produced from the 2-d mask layouts. Kinematic and other types of modeling should also be performed using these automatically produced 3-d models. Sandia is aggressively pursuing these challenges.

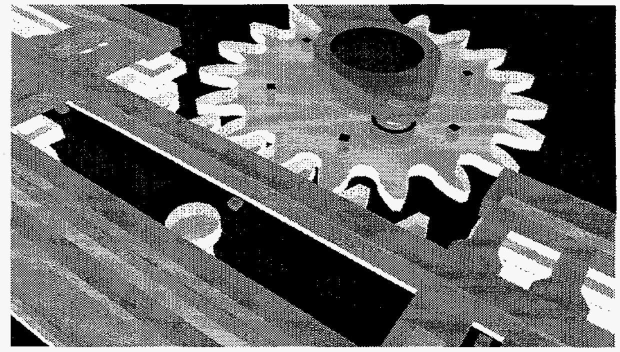

Figure 5. Three-dimensional MEMS models are automatically created from the 2-d CAD layout used to make the photolithography masks. This is done on a PC.

Reliability Assurance

The fact that MEMS are batch fabricated, with *no piece part assembly* (e.g. see Figs. 1,2), results in the mechanical systems being inherently more reliable than if they were comprised of many individually assembled components like traditional mechanical systems. In addition, polycrystalline silicon (the primary structural material) is an inherently strong and incredibly robust material. Nevertheless, the assurance of MEMS reliability remains a challenging task for several reasons.

MEMS are microscopic in size, resulting in the relative magnitudes of forces being very different than in the macroscopic world. Forces associated with interacting surfaces often dominate, hence many yield and reliability issues become closely related to tribology and adhesion. In general, mechanical failure mechanisms can be very different at microscopic size scales, and they are very different from IC failure mechanisms even though they are fabricated similarly. Neither of the traditional reliability tool suites for either macroscopic mechanical systems or microscopic electrical circuits is suitable for the unusual world of MEMS. Because of this, Sandia is providing leadership to support the development of the critically needed reliability assurance infrastructure.

Model-based Operational Methods

The use of model-based operational methods is important for several reasons. [8] Unnecessary failure modes and irrelevant failure mechanisms can directly result from improper operation. For example, microengine stop/start endurance has been improved 5 orders of magnitude just by using model-based drive signals. [9] Model-based operational methods are also required to make quantitative assessment of device or system performance. By combining model-based operational methods with quantitative performance measurements, Sandia has identified numerous failure mechanisms and has made significant improvement in several performance attributes. For example, specific design enhancements were identified for a microengine that improved its operational control by nearly an order of magnitude. It is only when the basic operation of devices is properly understood that the far more challenging issues associated with reliability assurance can be addressed.

High-volume Characterization

While test equipment for performing routine high volume testing of ICs is commonplace, the hardware and software infrastructure for characterizing MEMS is virtually non-existent. This infrastructure is essential for monitoring the state of production lines and for the qualification of product. To begin addressing this need, Sandia has developed a multiple-packaged part test capability for acquiring statistically significant quantities of data. [10] It can control 256 devices, and acquire data from each using optical techniques. The analysis of probability distributions for device failures in different operational configurations has revealed considerable insight into failure modes. Further advances in both hardware and software development are needed to make high-volume data acquisition for MEMS a routine task.

Environmental Effects/Packaging

Unlike passivated ICs, MEMS performance and reliability can be far more dependent on environmental effects and packaging issues. Because of this realization, Sandia is aggressively pursuing, at a fundamental level, understanding exactly how environmental parameters (such as humidity) impact device performance and reliability. In addition to the basic science, development of the essential characterization infrastructure (designs, hardware and software) is a priority, with collaborations being developed with universities and industry.

Summary

The successful commercialization of MEMS, which is critical to their implementation in government applications, requires major challenges to be overcome in the areas of design realization and reliability assurance. Sandia National Laboratories is providing leadership regarding how to overcome these challenges to companies, universities, and government agencies. This leadership is provided in the form of exceptional technical advances in key areas, the establishment of productive collaborations, and the appropriate, controlled dissemination of certain capabilities. In particular, an enabling suite of design tools has been developed and is being distributed, and access is being provided to an enabling suite of reliability capabilities as they are developed.

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