ADVANCING MEMS TECHNOLOGY USAGE THROUGH THE MUMPS (MULTI-USER MEMS PROCESSES) PROGRAM

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Abstract

In order to help provide access to advanced MEMS technologies and lower the barriers for both industry and academia, MCNC and ARPA have developed a program which provides users with access to both MEMS processes and advanced electronic integration techniques. The four distinct aspects of this program, the Multi-User MEMS Processes (MUMPs), the Consolidated Micromechanical Element Library, Smart MEMS and the MEMS Technology Network will be described in this paper. MUMPs is an ARPA-supported program created to provide inexpensive access to MEMS technology in a multi-user environment. It is both a proof-of-concept and educational tool that aids the development of MEMS in the domestic community. MUMPs technologies currently include a 3-layer polysilicon surface micromachining process and LIGA processes that provide reasonable design flexibility within set guidelines. The Consolidated Micromechanical Element Library or CaMEL, is a library of active and passive MEMS structures that can be downloaded by the MEMS community via the internet. Smart MEMS is the development of advanced electronics integration techniques for MEMS through the applications of flip chip technology. The MEMS Technology Network or TechNet is a menu of standard substrates and MEMS fabrication processes that can be purchased and combined to create unique process flows. TechNet provides the MEMS community greater flexibility and enhanced technology accessibility.

Introduction

Over the last decade silicon process technology, synonymous with integrated circuit processing, has been increasingly applied to the field of micromechanics, leading to the emerging field of MEMS (microelectromechanical systems). The extensive characterization of silicon processes by the IC industry, integrated with silicon's high Young's modulus and yield-strength, high thermal conductivity and low thermal expansion coefficient makes it one of the best understood and well suited materials available for coupled electronic and mechanical applications.

MEMS is an enabling technology, which partially accounts for the projections of 10 - 20% annual growth and the potential of a greater than \$8 billion market by the year 2000[1]. Current market estimates of approximately \$1 billion are possibly low since MEMS are already being incorporated into much more complex systems. Due to the enabling nature of MEMS and because of the significant impact they can play on both the commercial and defense markets, the federal government has taken special interest in nurturing growth in this field. One of the many ways this is being accomplished is through the MCNC MEMS Infrastructure program, supported by the Advanced Research Projects Agency (ARPA).

The MEMS Infrastructure program was established in 1993 to provide low-cost, easy access to advanced MEMS technologies. By lowering the barriers to the technology, it is hoped that the cost (both time and dollars) of developing and incorporating MEMS into new applications will be significantly reduced. There are three key components to the Infrastructure program; the Multi-user MEMS processes (MUMPs), a publicly-accessible standard element MEMS library and the generation of Smart MEMS through the use of flip chip technology. This Infrastructure base has been expanded through the MEMS Technology Network or TechNet. TechNet consists of two components, a wafer inventory of standard substrates common to MEMS fabrication and a menu of common process modules that allow users to piece together unique MEMS processes for more overall fabrication flexibility than offered in MUMPs. These activities are described below.

The Multi-User MEMS Processes (MUMPs)

As with integrated circuits, the cost of MEMS devices benefits from the leveraging of batch fabrication technology. Even so, the costs of micron-scale silicon processing is enormous. Building, maintaining and operating a cleanroom with knowledgeable workers can out price most universities, small and even medium-sized companies with interest in developing and/or commercializing MEMS technology. Commercial prototyping services are available but the cost of developing a full prototype can easily exceed $250K. As is often the case, MEMS fabrication is too costly for individuals interested in experimenting with this technology. As a result, the broad dissemination of MEMS technology is inhibited and the pool of creativity contributing to new and potentially lucrative products is restricted. It is these access and cost barriers to MEMS development that prompted ARPA and MCNC to establish a program of multi-project micromachining processes.

By providing an inexpensive route to MEMS fabrication technologies, the MUMPs program has filled two important niches. First, MUMPs provides cost effective proof-of-concept fabrication. This is particularly important for small (and even large) companies where R&D funds are limited and providing some kind of physical evidence beyond the "idea stage" is a prerequisite to further project funding. Once ideas have been displayed through the MUMPs process, users may wish to take their ideas further to the prototyping stage. Second, MUMPs provides a excellent, low-cost, educational tool. Since MEMS is, in many ways, still in its infancy, there is plenty of room for growth. Many universities are beginning to develop programs in MEMS. Small companies and government agencies interested in MEMS may find themselves relegated to reading journals but never testing their knowledge because of fabrication costs. The low cost of the MUMPs program gives these individuals an opportunity to learn more about MEMS technology and a means of testing their ideas.

The MUMPs program currently offers access to two distinct MEMS technologies: polysilicon surface micromachining and LIGA (hereafter referred to as LIGAMUMPs), which is provided in conjunction with the University of Wisconsin.

MUMPs

Polysilicon surface micromachining encompasses many of the same fabrication techniques as traditional silicon IC fabrication where layers of CVD films are deposited and subsequently patterned using photolithography and plasma etch techniques. Alternating layers of silicon dioxide and polysilicon are deposited so when all the layers have been patterned, the silicon dioxide can be etched away with hydrofluoric acid leaving only the polysilicon structures behind. The chief benefit to this process is the ability to fabricate moving parts on a silicon substrate. The MUMPs process provides two layers of structural polysilicon and a third layer of thin polysilicon that serves as an electrical ground plane or electrode. Devices fabricated in this way are typically several microns in thickness. With some devices having in-plane dimensions of greater than 500 μm, surface micromachined devices can take on a two-dimensional appearance. Nevertheless, the mechanical strength of polysilicon films makes such structures surprisingly robust.

Table 1 MUMPs (polysilicon) process specifications

Mask Level	Nom. Geometry	Material	Comments
Poly 0	3.0 μm	0.5 μm poly	Ground plane, low stress poly
Dimple	3.0 μm	-	0.75 μm dimple into first oxide
Anchor 1	3.0 μm	2.0 μm PSG (1st oxide)	Creates poly 1 anchors
Poly 1	3.0 μm	2.0 μm poly	First structural layer
Poly1_Poly2_Via	3.0 μm	0.75 μm PSG (2nd oxide)	Creates vias between poly 1 and poly 2
Anchor 2	3.0 μm	2.75 μm PSG (1st & 2nd oxide)	Creates anchor for poly 2
Poly 2	3.0 μm	1.5 μm poly	Second structural layer
Metal	3.0 μm	0.5 μm Cr/Au	Evaporated metal

The MUMPs process provides seven different films (layers) with which to build devices. These films are silicon nitride, poly 0, first oxide, poly 1, second oxide, poly 2 and metal. Table 1 describes these layers, their purpose and their associated lithography levels. The purpose of the
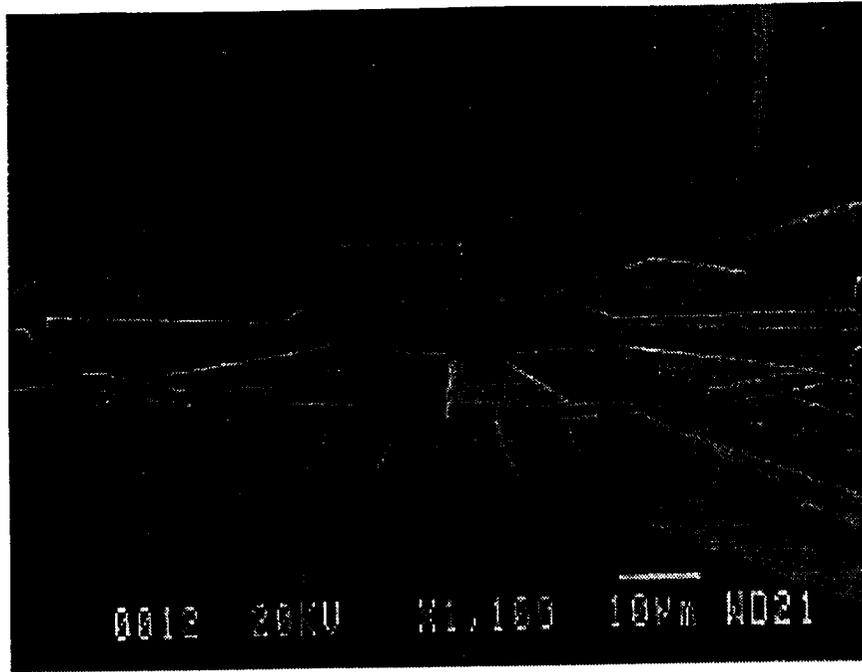
Figure 1 SEM of a micromotor fabricated using the MUMPs process. The rotor is approximately 80 μm in diameter and the rotor-stator gap is 2.0 μm.

Nitride   1st Oxide   2nd Oxide   Metal

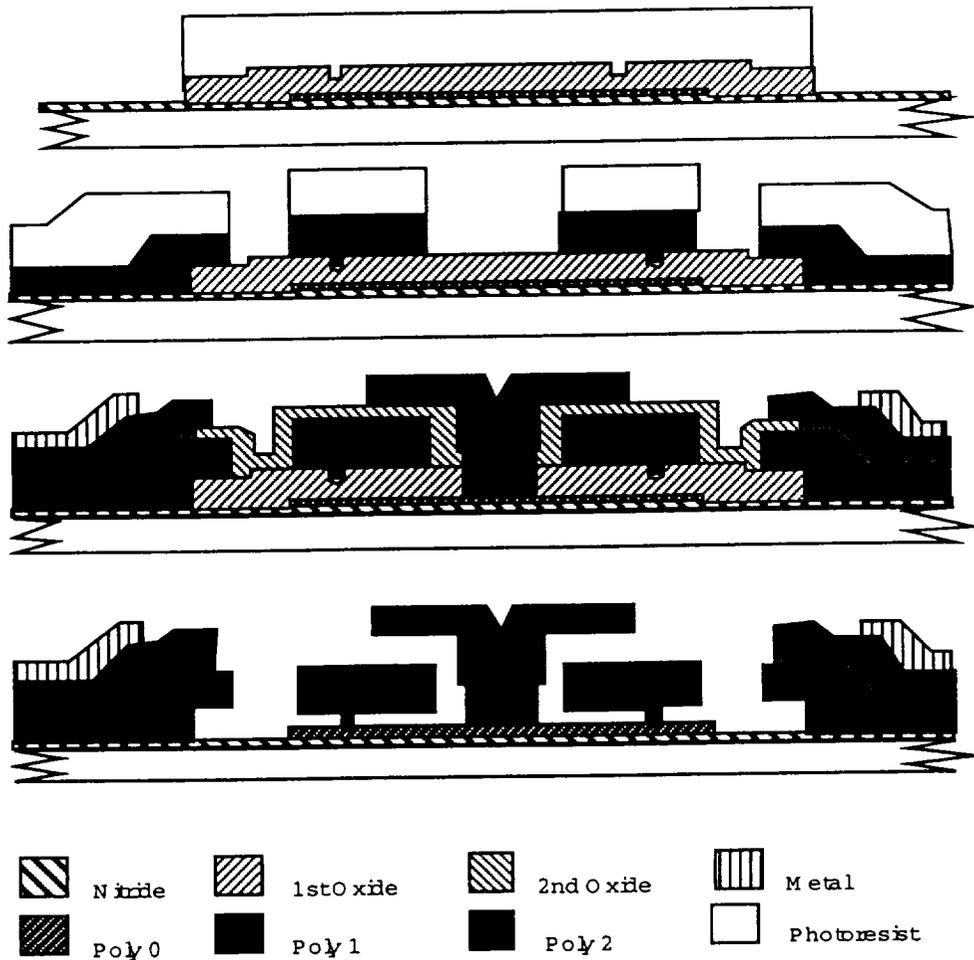Poly 0   Poly 1   Poly 2   Photoresist

Figure 2 MUMPs 3-layer polysilicon process flow for fabricating a micromotor.

oxide and polysilicon films has been described above. The silicon nitride film is a blanket layer that serves to isolate all structures electrically from the substrate. The metal layer serves two purposes, it provides electrical contact to the polysilicon simplifying wire bonding and second, it provides a reflective surface for optical applications. Figure 1 shows a scanning electron micrograph of a salient pole micromotor[2] fabricated using the MUMPs process. Figure 2 illustrates the progression of layers used to build the micromotor.

LIGAMUMPs

LIGA, a German acronym which translates to Lithography, Electroforming and Injection Molding, was developed in Germany in the 1980's[3] and has slowly gained wide-spread interest. There are two key factors to LIGA's attractiveness–the ability to mass-replicate high aspe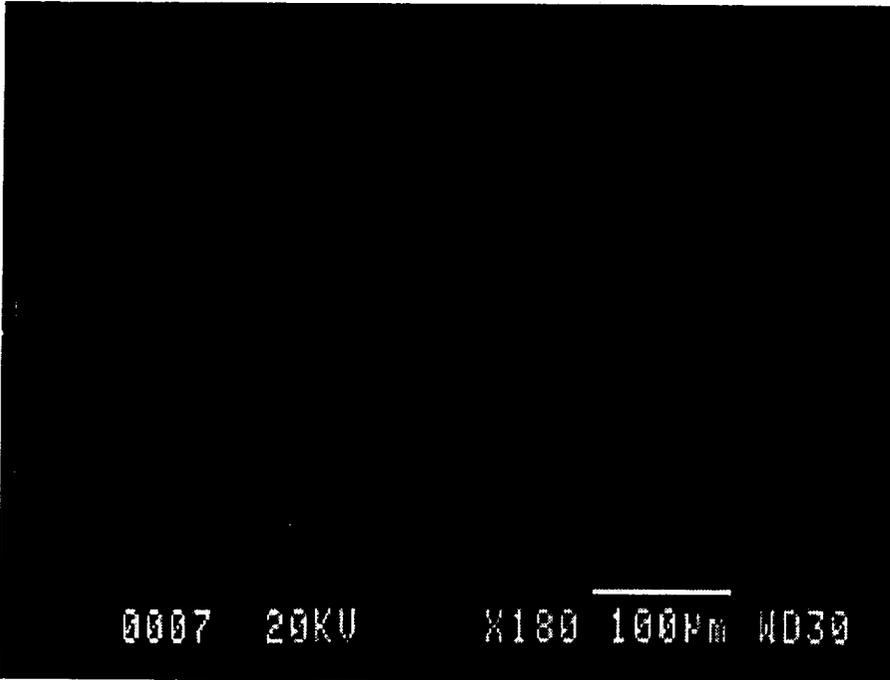ct ratio structures out of metals, polymers and ceramics, and the ability to fabricate structures which can be assembled with a high degree of precision. To produce LIGA requires the use of an extremely energetic, highly collimated light source, which restricts its practice to those facilities with access to x-ray synchrotrons. The synchrotron generated x-rays act to expose a thick layer of PMMA (polymethylmethacrylate) through an x-ray mask of high Z material. The x-rays provide deep exposure of the PMMA as well as excellent edge acuity (eg. 0.1 μm in a 400 μm tall structure). Once exposed, the PMMA becomes soluble in certain solvents. By "developing" in special solvent mixtures, the unexposed PMMA is left behind forming structures that can be used as-is or as an electroforming template for metals. After plating the PMMA template is removed leaving behind stand-alone metal structures. These structures can then be released from the plating base or used as injection molds for mass replication. Figure 3 shows a stator housing of nickel formed using the LIGAMUMPs process performed at the University of Wisconsin.

Figure 3 Stator housing fabricated using LIGAMUMPs process. Structures are electroplated nickel, 150 μm in height.

## Consolidated Micromechanical Element Library

The Consolidated Micromechanical Element Library (CaMEL) is a library of MEMS cells and is similar to standard cell libraries that proliferate in VLSI design. The CaMEL library consists of two independent parts, the nonparameterized cell database and the parameterized micromechanical element library. The aim is to provide MEMS cell libraries that are useful for novice MEMS designers, as well as experienced ones. Both libraries are intended to assist the user in the design and layout of MEMS devices and it is assumed that the user will modify and customize these elements using a suitable mask layout editor.

The nonparameterized cell library is a database of MEMS designs in various process technologies contributed by different sources. It is a resource of working MEMS devices and structures. The library browser, DBRead, permits the user to peruse brief descriptions of the cells and select desired ones. The selected cells can then be retrieved from the database in either Caltech Intermediate Form (CIF) or

CALMA GDS II format. A companion program, DBSubmit, allows designers to submit MEMS designs for inclusion in the database along with the accompanying process information. Both programs are written in the Practical Extraction and Report Language, PERL. Cells currently available in the library include designs for MUMPs, UCB 2 poly, and LIGA processes.

The parameterized micromechanical element (PME) library is a set of generators that allow users to create customized versions of commonly used elements in a quick and easy manner. The PME library also provides a framework for writing cell generators. It enables the generators to be relatively process independent and allows limited cell hierarchy. Designs can be generated in CIF, GDS II, or PostScript output formats. Technology dependent design rules are read in from an environment specified technology file. The library provides various geometric primitives and a set of available generators. Various types of elements are available, including active micromechanical elements, passive micromechanical elements, test mechanical structures, and electrical elements.

The PME input is provided in an ASCII text file and defines cells by calling generators with desired parameter values and then placing instances of defined cells at chosen locations within the top level cell. Instances of defined cells can be reflected, translated, or rotated through arbitrary rotation angles.
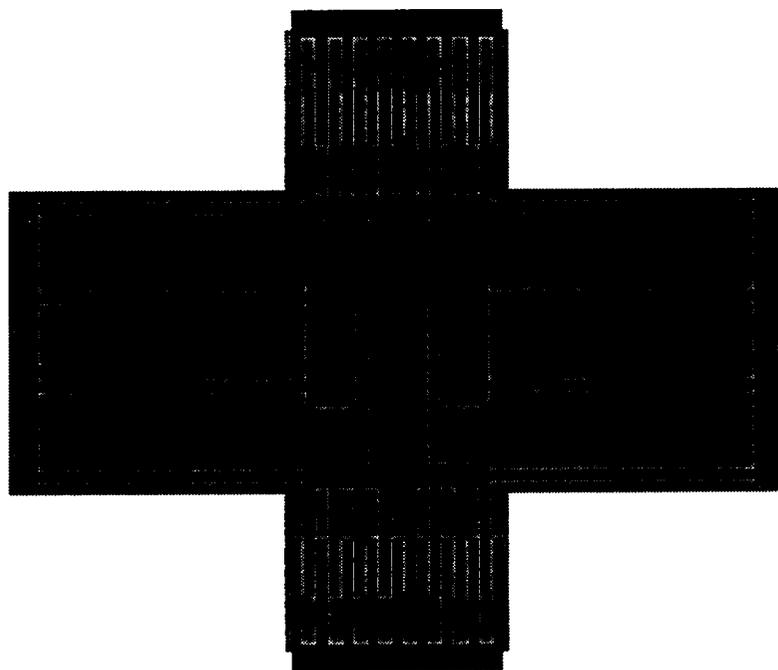

```
/* Linear comb resonator */
PME p1,p2;
/* Create comb and suspension */
p1=lcomb1(98,12,14,60,4,3,30,
          comb);
p2=lfbs1(150,4,50,12,30,25,12,
         98,suspension);
/* Place cells for resonator */
instance(p1,'*',0,0,75);
instance(p1,'*',0,0,-75);
instance(p2,'*',0,0,0);
```

Figure 4 Example of linear comb resonator generated using the PME library.

Figure 4 is an example of a linear comb resonator generated by the PME library and its associated input file. It is generated using the first structural layer (poly 1 in the MUMPs process) using the **lcomb1** linear comb drive and **lfbs1** linear folded beam suspension. The fingers in the comb drive are 4 μm wide with an airgap of 3 μm, and beams in the suspensions are chosen to 150 μm long and 4 μm wide.

Smart MEMS: Electronics integration for MEMS

There has been a growing interest in placing electronics closer to sensors and actuators to improve their performance. Among the several approaches that have been demonstrated are hybrids and embedded electronics. The hybrid approach, in which the different chips including electronics, sensors and actuators are placed in a single package and connected by wire bonding, has long been the industry standard. This approach is flexible with few restrictions on the types of usable electronics and substrates. However, hybrids are not batch fabricated, can suffer from system performance degradation due to stray or large capacitance and also result in increased size of the integrated system[4]. A recent approach[5,6] has been to build MEMS sensors and actuators on top of underlying electronics on the same substrate. This embedded approach is suitable for batch processing and results in significant improvement of

performance. However, it involves a large number of processing steps that can increase processing complexity and reduce yield, driving up the costs.

Flip Chip MEMS

Flip chip MEMS combines the advantages of the hybrid and embedded approach. The electronics and the MEMS are batch fabricated on different substrates and are then connected using solder bumping. Flip chip has been successfully used to connect IC chips to printed circuits or substrate carriers for almost 20 years. In conventional flip chip attach, the IC chip is turned upside-down (i.e. *flip chipped*) and an array of solder bumps on the chip are joined to a matching array of solder wettable pads on the substrate. This conventional approach has been modified to facilitate the connection of the MEMS chip to the electronics chip, taking into account the mechanical or 'released' nature of MEMS chips (fig. 5).
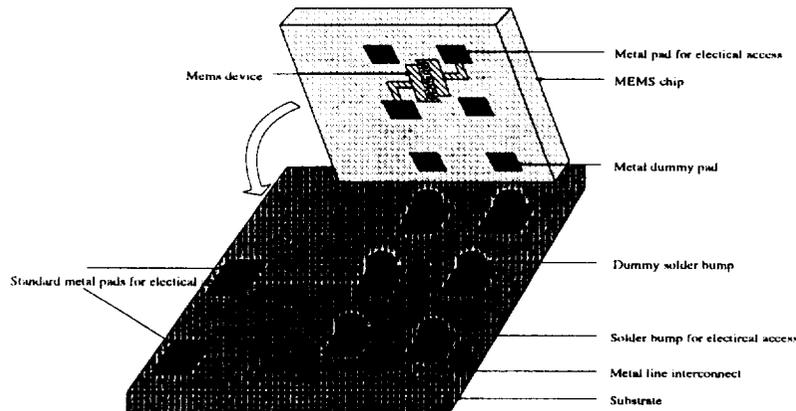
MCNC is a world leader in the development of flip chip process technology for MCM's, and is the site of the ARPA-supported Flip Chip Technology Center. As part of the MEMS Infrastructure program we are investigating the various issues involved in bump attaching both surface and bulk micromachined devices to different types of substrates, including silicon, quartz, Pyrex and GaAs. Methodologies for the handling of released MEMS structures and design rules are being developed to allow the MEMS community to access this advanced integration technique for the production of Smart MEMS systems.

Figure 5 Schematic of flip chipped MEMS and substrate die

Electromechanical Control System

The Electromechanical Control System (ECOSYS) is a program to facilitate the fabrication of MEMS systems including the electronics. A standardized IC controller with various functional blocks is currently under production. The aim is to implement a system incorporating sensing, feedback, and control by allowing users to connect blocks and attach them to a MEMS device via flip chip. A limited degree of user programmability will be provided via external RC components to tailor the response of the blocks for the application. Interconnections to the MEMS elements will be via solder bumps and the parasitics introduced by the solder bump and pad will be accounted for in the design of the blocks.

Expanded Infrastructure–MEMS TechNet

Once proof-of-concept has been established using MUMPs, users often require larger numbers of prototypes for testing and evaluation than MUMPs can provide. An expansion of the current Infrastructure program is underway that is designed to provide users more flexibility to design and fabricate unique devices and also produce larger quantities as the need arises. The added flexibility is beneficial in cases were the uniqueness of a MEMS device may necessitate custom fabrication processes that are not provided by MUMPs.

The Expanded Infrastructure, known as the MEMS Technology Network or MEMS TechNet, will consist of two parts, the Wafer Inventory and the Process Modules. The Wafer Inventory will provide the MEMS community with a variety of standard films (and combinations of films) including low stress nitride, polysilicon and phosphosilicate glass (PSG). These wafers can be purchased and subsequently

processed at MCNC or elsewhere, giving the user the greater flexibility and capacity needed by more mature programs. The Process Modules will provide users with a menu of MEMS fabrication processes and sequences such as anisotropic wet etching (KOH or EDP), deep boron diffusion, wafer bonding and laser assisted etching. The focus of the modules is to give users a wide variety of fabrication technologies thereby allowing them to fine-tune their device processing. Many of these processes will be supplied by providers other than MCNC who have considerable experience with the process. MCNC will operate as a clearinghouse for the modules thereby simplifying the complex task of locating and purchasing such services.

Acknowledgments

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