THE 18mm² CLASSROOM

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ABSTRACT

We describe a MEMS course sequence based on Sandia National Laboratories' (SNL) SUMMiT V MEMS process. Over three semesters, our curriculum takes students who typically begin with no MEMS knowledge, to a level where they are capable of designing MEMS for cutting-edge research applications. The main tool is a customized AutoCAD-based MEMS layout system developed by SNL. This software incorporates the capabilities and limitations of the SUMMiT process, and includes a pre-defined library of useful and instructive components. Devices designed with this software and validated by an on-line SNL design checker may be manufactured at SNL's Albuquerque, NM facility. The SNL MESA Institute sponsors a yearly design competition for the universities in its University Alliance Program. In our first year of participation, Texas Tech student teams developed a micro X-Y stage with AFM-like cantilever probe, a microclock, a microchain and drive system, and two types of micromirrors. These devices, laid out on a 18 mm² (2.82 x 6.34 mm) module, were selected as the winning entry. Educational benefits for student competition participants include immersion in MEMS design and fabrication, familiarization with layout software and process and device simulation, and experience with working in tightly integrated interdisciplinary teams. Furthermore, the devices produced are themselves expected to have significant research value.

INTRODUCTION

The world of Microelectromechanical systems (MEMS) continues to expand, with increasing numbers of devices moving from the laboratory into commercial applications. Long-standing MEMS commercial success stories such as ink-jet printer heads, video displays, and accelerometers have been joined by pressure sensors and microphones in high-volume production. As the market expands, so does the demand for engineers and scientists who have the training and skills necessary to make important contributions to this burgeoning field. Accordingly, educators have the responsibility to incorporate both fundamental and advanced MEMS topics into undergraduate and graduate engineering curricula. Staying abreast of this continually advancing field without constant course overhauls is a significant task. One approach to doing so is to present students with a design challenge, based on a state-of-the-art fabrication process and incorporating current device applications. An essential component in such an approach is to select a standardized, but versatile, fabrication process with continually supported design and visualization tools.

Sandia National Laboratories has developed a polysilicon based fabrication sequence called SUMMiT V (Sandia Ultra-planar Multi-level MEMS Technology 5) that is ideally suited for this purpose. A total of five polysilicon layers are used, along with four layers of silicon dioxide used as a sacrificial layer to build complex electromechanical devices. SUMMiT V is extraordinarily capable, and has been used to construct micro engines, gears, and hinges, and many other dynamic mechanical structures [1-4]. In order to expand the usage of their MEMS foundry, Sandia has initiated a University Alliance Program which allows universities access to design and visualization software tools for a one-time fee [\$5000 (2005)]. The design and visualization tools are proprietary

software AutoCAD plug-ins. AutoCAD layout tools are used to construct the two-dimensional masks used in the photolithography steps of the fabrication process. The SUMMiT V process has pre-defined thicknesses for each of the polysilicon and silicon dioxide layers. Essentially, the designer chooses the X and Y dimensions and Sandia constrains the Z dimensions of each layer. Figure 1 shows a cross section of the layers that make up the SUMMiT V process. The 2-D visualization tool allows the user to cross-section a part to see how it will fabricate. The top of the screen shows each layer of the photomask cross-sections. At the bottom of the screen, the SUMMiT layers can be added, etched, and finally released, one by one. Much empirical data allows the depiction of the topology to be remarkably similar to the final fabricated result. This tool is an excellent tool for showing students how the photolithography, deposition, and etch processes affect the final MEMS structure. 3D visualization and modeler tools are also included. The 3D visualizer provides a rapid, but not overly accurate rendering of the structure. The 3-D modeler renders a detailed and accurate picture, but can take several hours for large and complex devices. These tools promote rapid assimilation into the design environment, lead to new design ideas, and highlight fabrication problems and constraints.

The software tools include a library of pre-defined parts. These are primarily actuators and include a rotating drive known as a torsional ratcheting actuator (TRA) a displacement multiplier that can produce a 10X increase in motion, and a gear transmission. These and other library part can be utilized in its entirety simply by pasting it into the design area. This feature saves immense amounts of time and alleviates a designer from (sometimes literally!) reinventing the wheel when certain commonly used parts are needed. For example, instead of laboriously re-constructing a rotating drive from scratch, the designer can spend all her time designing the *device* that will utilize the circular motion. Rapid prototyping becomes much more feasible. A design rule checker is used to flag designs that do not meet minimum feature size, overlay guidelines, and other parameters. This helps prevent the most blatant mistakes, and decreases the number of design cycles needed to produce working devices.

INCORPORATION INTO TTU MEMS SEQUENCE

At Texas Tech University, we have developed a three-course sequence in microsystem design [5,6]. Beginning in 2000, and supported by a National Science Foundation Combined Research and Curriculum Development grant, a number of faculty have contributed to developing a laboratory-based multidisciplinary curriculum. A key aspect of the course sequence is *peer-mentoring*, with senior graduate students serving as leaders of small research teams, that accomplish the design, fabrication, integration, and testing of a microsystem compliant to specifications presented by faculty “clients.” We have worked to augment our laboratory-based courses with a classroom-based program offering similar characteristics and benefits, but at a lower cost. Since the fall of 2004, we have positioned our education efforts to leverage the enormous infrastructure represented by the SUMMiT design and fabrication system.

Since 2005, Sandia’s MESA Institute has sponsored an annual SUMMiT MEMS design competition for member schools in their University Alliance Program [7]. A single wafer die is segmented into eight 2.82 x 6.34 mm *modules*. Each school is allowed to submit a module, which may contain several MEMS devices. The top eight designs—as judged by a panel assembled by Sandia—are fabricated and the parts are distributed to the member schools. The criteria for winning designs include integration of multiple layers, usefulness for educational demonstrations, and uniqueness of design. Up to one-third of the module may be used for non-student designed devices. Completed devices are typically received three to four month after the designs are submitted and pass design checks. Schools receive ~50 of their own modules as well as modules designed by other schools. The fact that student-designed devices are actually available for characterization and test, using one of the most advanced MEMS fabrication processes in the world, makes SUMMiT V-based education tremendously appealing. Additional benefits are realized by creating designs that carry significant value to university research programs.

Figure 3. AutoCAD design of microClock and SEM image of fabricated device.

Figure 4. (a) microAFM stage assembly, arm and scale. (b) spiral gear and cam assembly; one each for X and Y stage (c) pin assembly that allows cantilever arm to be scanned by stages (d) end of cantilever arm; a single dimple is on the underside of the tip.

Our first semester course, Introduction to Microsystems (MEMS I), is used to give students a broad overview of microsystem technologies and covers many fabrication processes besides SUMMiT V and similar polysilicon-based technologies. However, the students are instructed on the use of the SUMMiT AutoCAD design tools and are required to complete gradually more complex designs through the course of the semester. The students are also required to carry out numerical simulation (using MATLAB or ANSYS) of a key aspect of their design. Interim and final presentations are given by the students. The most promising designs are carried forward in to the subsequent classes, Introduction to Microsystems II and III (MEMS II and III).

MEMS II is completely project based and requires individual students or small groups to design and simulate complex MEMS. In our peer-mentoring approach, Experienced MEMS III students guide the research efforts of small groups of MEMS II students. Projects are developed in conjunction with faculty and are specifically chosen to benefit real research needs. The first two iterations of the Sandia MEMS Design Competition have had submission deadlines approximately two thirds of the way through the spring semester. This timeline fits our course offering system quite well (Fall: MEMS I; Spring: MEMS II/III).

RESULTS AND DISCUSSION

In this paper, we mainly report on the results of the first year (2004-2005) that we made SUMMiT V and the Sandia Student Design Competition the focus of the curriculum. We also comment on the enhancements made in year two (2005-2006), which is still a work in progress. The majority of the work that went into the 2005 design competition module was completed in a ten week span by a class of ten students that included undergraduates and graduates. The students were tasked with developing ideas on what to design. To do this, they carried out literature searches and in some cases, contemplated the needs of their own graduate research. Prior work indicated only a limited amount of published work utilizing the SUMMiT V process. Some examples included a microfabricated chain, micromirrors, and accelerometers. The first four weeks of the semester was spent trying to narrow the list of potential projects to those that would fit in the remaining six week timeframe. Although some compelling devices resulted, more time should have been devoted to design and simulation. This is an aspect currently being addressed. Ultimately, five devices made it onto the final TTU module, shown in Figure 2.

Figure 5. *microChain, sprocket and guide as designed in AutoCAD and as fabricated (SEM image).*

The five devices fell into two categories. First (the micro clock, micro AFM, and micro chain) are highly complex mechanical designs to mechanically involved for device-level simulation. The others (micromirrors) are relatively simple mechanical designs, and were computer simulated. A brief description of each device is given in order to demonstrate the capabilities of the technology, as well as illustrate the range of possible devices that can be fabricated on one module. The resulting designs show that highly skilled and motivated students can produce complex devices in a relatively short time frame.

The first device was a clock designed by an undergraduate student with prior AutoCAD knowledge. He designed the clock for his final project in MEMS I and made significant improvements to it for MEMS II. Being adept at AutoCAD or another CAD program greatly expedites the design process. Being able to effectively use AutoCAD is an important tool for many engineers and scientists regardless of the size of devices being designed. Therefore, we regard the acquisition of AutoCAD proficiency to have long-term benefit to the student, regardless of whether or not they continue on in the MEMS design field.

The micro clock, as shown in Figure 3, was designed to be one of the world's smallest mechanical clocks. A single TRA is geared down to run separate second, minute and hour hands. Additional levels were added to gears in order to change levels and to allow hands to be fabricated. This design was an important first step in learning how to use the design tools to construct devices. The design used mostly standard parts (gears, TRA's), but some were modified to fit this application. Students quickly gain insight into the design environment by modifying existing designs found in the standard parts library. Occupying an area of 4 mm^2 , more than fifty of these clocks will fit in the area of a penny. A single TRA is used to drive an 11 gear drive system with 3 additional gears used to rotate the second, minute, and hour hands. Compound gears were specially designed to accomplish significant ratio changes. The device design allowed room for artistic embellishes, such as TTU's "Gun's Up" hand gesture used on the clock's second hand. Effective MEMS design requires large amounts of creativity and we encourage students to develop designs that are first and foremost functional, but incorporate aesthetic elements that enhance human interaction with the devices.

The Atomic Force Microscope (AFM) has become a ubiquitous characterization tool for measuring topology and other surface phenomena. An atomically sharp tip is scanned across the

surface of a sample. Interactions between the tip and the surface are measured allowing quantification of many surface properties. This analytical tool served as the inspiration for the device shown in Figure 4. A student designed an X-Y stage, driven by two TRAs, which can be used to position/scan a pseudo-AFM cantilever arm which included a $1.5 \mu\text{m} \times 1.5 \mu\text{m}$ polysilicon dimple (tip) at the end and on the underside of the arm. These dimple elements are typically used as anti-stiction structures and are available for incorporation on three of the polysilicon levels. The cantilevered arm is connected to a flanged pin held between slots in the X and Y stages. The travel is $110 \mu\text{m}$ in both X and Y. The layout allowed the arm to be extended off the edge of the chip, possibly to access an external Z-stage where a sample could be placed. Due to TRA limitations (i.e., uni-directional rotation), the arm cannot be retracted at this juncture. During operation, the TRAs are used to drive a gear with a spiral slot etched into it. A flanged pin that is positioned in the slot is connected to the X or Y stage and is pushed away from the center as the gear turns. The AFM arm is connected to a central pin that is held between the X and Y stages. A scale is used to indicate arm position.

The basis of the mechanical design had its origins in a macroscale mechanical system that took rotational motion and converted into linear motion [8]. With some modification and allowing for the limit on the number of polysilicon levels, a microscale analog was designed that allows for precise X and Y motion. Although an AFM-like arm was attached, the motion generating part of the design could be attached to a stage or some other structure where X and Y motion would be needed.

A 60 link micro chain, tensioner, and drive system was also included on the module. The chain is composed of $50 \mu\text{m}$ links giving an overall chain length of 3 mm and a width of $20 \mu\text{m}$. Figure 5 shows the 3D AutoCAD design as well as an SEM of the fabricated structure. The fidelity between the AutoCAD 3D rendering and the actual device is quite good and get be analyzed by the students to gain further insight into the realities of the fabrication process. A torsional ratcheting actuator (TRA) is connected to a drive sprocket by a gear train and is designed to drive the chain along a path delineated by ten custom idler sprockets in addition to the single drive sprocket and a linear tensioner. The linear tensioner is designed to remove slack from the released chain and force contact with the drive system. A second TRA is implemented with a rack and pinion system to move the tensioner and provide the ability to remove up to $200 \mu\text{m}$ of slack. The entire device occupies a surface area of under 4 mm^2 including the relatively large TRA's. A previous SUMMiT chain was unable to be driven due to low power and high mechanical resistance. The students' design reduces the contact area inside the link hub and therefore, potentially reduces friction and stiction. This system was designed by finding alternatives to the pin joint undercut used in most SUMMiT hub designs. In addition, the design incorporated an actuator with more power than the previous system. An automated tensioner is included that improves upon the previous device that had to be tensioned by hand, using a probe.

Two micromirror arrays were designed to meet research needs of students participating in the class. Their designs were guided by systems that the MEMS devices would be integrated with. The first type of micromirror is a linear, array of electrostatically actuated torsion micromirrors that incorporate multiple electrodes for static feedback control. A number of preliminary designs were simulated using a Finite Element Modeling software package (ANSYS 8.0) to determine a suitable design for the fabrication process. The mirrors were designed to produce both translational and torsional analog motion. The pitch of the array was chosen to correspond to the mean distance between two consecutive waveguides of a reflective folded arrayed waveguide grating multiplexer (32 microns). Each mirror,

Figure 6. *SEM images of (a) Torsion micromirror (b) piston micromirror.*

fabricated at the poly3 level of SUMMiT, is 25 μm x 25 μm and is supported by 400 μm long springs to allow relatively low actuation voltages. To prevent excessive translational motion, two stops are built below the springs using poly1 and poly2 at a distance of 20 μm from the end of the mirror. The mirror will translate vertically and then rotate once the springs land on the stops. A total of four bond pads are used to form electrical contacts to each mirror. One pad is used for each of the two driving electrodes and one is connected to the sensing electrodes. A common bond pad is connected to all the mirrors. Thus, the translational motion is achieved by activating both drive electrodes while rotational motion is achieved by activating one drive electrode. The voltage at the driving electrodes will be varied analogically depending on the feedback signal from sensing electrodes, given the position of the mirror at the previous state.

Analog amplitude modulation of light can be used to make a variable optical attenuator and add-drop multiplexer using the Mach-Zehnder interferometer principle. For this principle to apply, it is necessary to precisely control the optical-path lengths of the two interferometer arms. Thus, the exact control of the movement of the translational micro mirrors which vary the optical-path lengths is required. The mirror is required to translate by $\frac{1}{4}$ of the wavelength of the light used; in this case, 1.55 μm . Therefore, the mirror translation movement needs to be 0.5 μm to ensure controllability over the required range. The mirrors were designed to have a control voltage below 50 volts. The pitch of the mirrors was set to 250 μm to match the pitch of the optical device it will be coupled with. Based on these requirements, the students designed an 84 μm square micro mirror with serpentine support springs. Various electrode designs have been incorporated to test different structural support geometries. ANSYS simulations were used to explore the mirror design space and electrode functionality.

During the spring 2006 semester, MEMS II students have been working to assemble testing systems for these devices. Due to a small, but important design error, the TRA's were shorted on the original module preventing electrical actuation of the devices. Sandia has re-manufactured the devices with a correction and the new parts will be received later in the spring semester. Where possible, a sharp probe has been used to manipulate the various mechanical structures to test some aspects of functionality. The microchain slides very easily over the surface and moves in an analogous manner to macroscale chains. The piston micromirrors are being tested using an interferometric microscope and probe station. Students will be able to compare the design goals with the actual performance of the mirrors. Testing modules designed by previous classes is a critical aspect of this work that allows students to get hands-on experience with real devices, and allows critical analysis of prior work. Testing actual devices can give important insight to current design projects.

CONCLUSIONS AND FUTURE WORK

We have successfully transitioned our MEMS course sequence to incorporate the design, fabrication and testing of SUMMiT MEMS devices. We believe we have developed a productive teaching cycle in which students first understand and reverse engineer existing student-designed devices, then develop and design their own. This approach builds student confidence, and allows accumulation of expertise and design of devices of increasing sophistication and research value. This work illustrates an exciting avenue for giving students an in-depth educational and research experience on complex microscale systems. In addition, it demonstrates the relatively rapid MEMS prototyping capabilities of the SUMMiT fabrication system. Further benefits of this educational activity include nurturing of student creativity and exploration of projects of personal interest, learning about

semiconductor and MEMS processing steps and constraints, utilizing 3D CAD tools, utilizing software simulation tools, and building devices to support the research of individual students. The design competition aspect fosters excitement and imposes hard deadlines—both aid in motivating the class. The students involved in the first iteration received significant publicity for winning the Sandia competition, which will continue to spur future classes to match or surpass their accomplishments. The inherent research value of many of the devices also leads to student co-authorship on archival journal papers.

One of the main educational paradigms that we developed during the previous iteration of the MEMS course sequence was the forum for interdisciplinary student training using peer mentoring and a “client”-driven project model. In the second year of the SUMMiT-based courses, we are developing devices for specific applications that meet the needs of “client” research endeavors. Although the scope is limited to a few devices on the current module, we will use the lessons learned through this process to increase this number in subsequent years.

A group of students is currently designing microcantilever arrays that can be functionalized through wet chemistry techniques and utilized in standard sensing configurations using an optoelectronic system. This project requires significant interaction with researchers in chemical engineering and chemistry. Projects like this draw in MEMS students outside the typical electrical and mechanical engineering disciplines, by solving real problems using micro and nano technologies.

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