AC 2011-2264: "MUMPS" MULTI-USER-MEMS-PROCESSES AS TEACHING AND DESIGN TOOLS IN MEMS INSTRUCTION

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"MUMPs" Multi-User-MEMS-Processes as Teaching and Design Tools in MEMS Instruction

Abstract

The paper describes use of "MUMPs" (Multi-User-MEMS-Processes) as a platform to teach Silicon based MEMS technologies and to implement design projects in a new interdisciplinary senior level undergraduate engineering course offered at the University of Southern Maine. In addition to the standard lectures/reading/homeworks/tests routine of a typical coursework students in this class are assigned to design, both as homeworks and as individual class term projects, various sensors using integrated circuit layout design tools and standard Silicon MEMS technologies available and known as "MUMPs" (Multi-User-MEMS-Processes). The Silicon-On-Insulator version of MUMPs which is named "SOI-MUMPs" was chosen for the final projects. Thanks to the funding received from NASA/MSGC successfully completed designs are combined to form a multi-project MEMS chip and sent out to be fabricated. The multi-project MEMS chips fabricated are packaged and wire bonded in house for testing. In the first year offering of the course "Impact" or "Crash" Sensors were designed and fabricated. In the second offering of the course "Capacitive Acceleration Sensors" were designed. On the side, senior projects assigned have created the platforms to test these sensors, namely, an accelerator which can create centrifugal g-forces up to 20g's and a capacitive sensor computer interface with femtoFarad resolution.

Examples of designs, simulations, test equipment and setups used and the results obtained will be presented to share this experience with the faculty and students attending the conference from other institutions.

1. Introduction and Background

The paper describes some of the standard MEMS technologies and services available on the market at reasonable levels of cost which can be used to introduce real design experience in MEMS courses delivered at undergraduate as well as graduate level in engineering.

The term "MEMS" is an acronym used for Micro-Electro-Mechanical-Systems. MEMS are integrated devices which have components with dimensions ranging from tens of micrometers to millimeters, and with minimum feature sizes as small as a micrometer. Unlike the well known machine shop machining technologies which produce one part at a time, MEMS technologies use micromachining or microfabrication techniques adapted from the well developed Silicon integrated circuit fabrication technologies. Silicon based MEMS technologies, just like the Silicon integrated circuit technologies they evolved from, do not only achieve precision at micrometer scale via microfabrication, but more importantly, offer extremely cost effective batch fabrication with thousands of fully functional Micro-Electro-Mechanical-System chips on a wafer of Silicon, with each chip incorporating hundreds to millions of MEMS components to deliver various functionalities. The most well known MEMS products on the market are the acceleration (impact) and pressure sensors used ubiquitously in vehicles, and the DLP (Digital Light Projection) devices used in large screen HDTV displays and digital projectors.

MEMS is a very interdisciplinary subject. It involves various disciplines of engineering and science, electrical engineering, mechanical engineering and physics (optics) primarily for innovation and design, materials science and chemistry for fabrication processes, and all the fields for applications in consumer products, instrumentation, sensors, biomedicine, etc. This interdisciplinary nature of MEMS creates many challenges as well as opportunities in the academia for introducing the subject at both graduate and undergraduate levels.

We have recently introduced an undergraduate senior level MEMS course as a technical elective primarily for electrical (EE) and mechanical engineering (ME) students. Topics covered include micromechanical structures, materials for MEMS and their thermal, electrical and mechanical properties, principles of microfabrication, micromechanics, electromechanical energy conversion and transduction. Basic electro-mechanical system blocks like beams, cantilevers, resonators, micro actuators are analyzed and their integration into the design of micro systems for applications in digital micro-mirror (DMM) projectors, acceleration and pressure sensors, RF and optical signal routers, micro pumps, micro motors and micro robots are discussed. In a new interdisciplinary subject with such a variety of engineering applications and extremely suitable for innovation of new products the author sees the need for and feels a responsibility to provide the knowledge, tools and experience to his students, the innovators and entrepreneurs of the next decade.

Thanks to a NASA grant from Maine Space Grant Consortium such tools and design experience could be provided in the MEMS courses offered.

2. "MUMPs" Processes and Design Tools

For a MEMS process to be adopted as an instructional tool it must (1) be affordable, (2) have standardized, complete and publicly accessible process flow, (3) be compatible with the in house design tools available, preferably those running on a PC platform, (4) be consistently available several times a year with fabrication run schedules announced long in advance for budgeting and planning, and (5) have quick turnaround times.

The MEMS fabrication service known as "MUMPs", the "Multi-User-MEMS-Processes" provided by MEMSCAP, Inc. (http://www.memscapinc.com) meets all the above and therefore was adopted for use in our MEMS classes. The facts that, (1) "MUMPs" services have initially been supported by US government agencies to foster innovation and development in MEMS technologies and MEMS education, and (2) it has been around over a decade, were reassuring for continuity.

The design tools used at our department are, (1) "L-EDIT" by Tanner EDA Products (http://www.tannereda.com/) and, (2) "MEMS Pro" a specialized version of L-EDIT specifically enhanced for MEMS design and simulation by SoftMEMS, Inc. (http://www.softmems.com/).

Both of these can run on PC platforms, therefore, they do not require UNIX environment which may call for specialized support and pose difficulties at some educational institutions.

L-EDIT is an integrated circuit layout and design tool and Tanner EDA offers it packaged as "Tanner EDA Tools" with SPICE circuit simulation and technology files for IC design. "MEMS Pro" is offered by SoftMEMS, Inc. and comes equipped with the setup and technology files specific to the "MUMPs" processes and a small MEMS components library which helps the beginner start a design with minimal setup and learning effort. "MEMS Pro" also comes with design rules built into the MUMPs technology files to check design rule violations and correct them on the spot. The 3D viewer and exporting of structures as dxf files and compatibility with ANSYS finite element simulation tools makes it possible to do electro-thermo-mechanical simulations of the designed MEMS structure.

"MUMPs" incorporates three main standardized MEMS processes, (1) "PolyMUMPs", a three-layer polysilicon surface micromachining process, (2) "MetalMUMPs", an electroplated nickel process; and (3) "SOIMUMPs", a Silicon-on-Insulator bulk micromachining process with through the wafer holes. In the MEMS class two of the three, namely, "PolyMUMPs" and "SOIMUMPs" processes are emphasized, both Silicon based, and both widely used by researchers and MEMS product developers for prototyping and innovation.

"PolyMUMPs" and "SOIMUMPS" processes, though both being Silicon based, have significant differences in both fabrication process and in the MEMS structure they produce. "PolyMUMPs" is an additive MEMS process. It employs stacks of thin layers of poly-crystalline Silicon, SilicondiOxide (SiO_2) and Metal all successively deposited on a single crystal silicon wafer which acts as a substrate. MEMS structure is built by using different patterns for each layer according to which the layer is chemically etched and shaped. The etching processes used can be wet (i.e. involving acid solutions) or dry which involves reaction with a gas in a RF generated plasma environment where atoms or molecules of the gas are ionized and energized. This "dry" Reactive Ion Etch, "RIE" results in highly anisotropic (directed) etching which creates vertical side walls and, therefore, is preferred in MEMS fabrication. PolyMUMPs process is a surface micromachined MEMS process since it employs thin deposited films and built on the surface of the substrate. SiO2 layers are "sacrificial". They are used to separate and support the active MEMS layers, namely, polysilicon and metal layers. Motion freedom of the parts made from these deposited silicon and metal layers are obtained by etch removal of the "sacrificial" oxide layers at the end of the process, thus releasing the active layers from each other as well as from the substrate. The "PolyMUMPs" process creates two polysilicon and two metal (gold) layers and a thin polysilicon layer affixed to the substrate with a thin silicon nitrite film underneath for mechanical support but electrically insulated. Nominal values of the thicknesses of the active and sacrificial layers typically range 1.5 to 2.0 micrometers. Therefore, after the release etching of the sacrificial layers, the active layers have about 2 um air separation. (Details of the process and specifications are given by Wilcenski [8].) This small separation can result in significant air friction and energy loss and degradation of performance in MEMS devices operating at high frequencies, such as MEMS resonators. In the PolyMUMPs process layers are conformally deposited on the layers previously deposited and patterned (see reference [8]). Since no planarization is done before depositing a new layer, the new layer can have surface topology and thickness variation which can render the process not suitable to make optical mirrors. However, with this process challenging designs including several different electrostatic micro-motors designs have been shown to be doable. (Sandia Lab's SUMMIT process employs Chemical Mechanical Polishing (CMP) planarization and is more suitable but an expensive alternative to PolyMUMPs.)

In most of our class design projects we employed the SOIMUMPs MEMS fabrication process. The SOIMUMPs wafers are essentially two single crystal silicon wafers bonded back to back on their <100> plane. A 1µm oxide layer lies between the two wafers to insulate the device layer from the substrate while a thinner layer of oxide is deposited on the backside. The top wafer is etched to a thickness of 10µm, and then doped with phosphorus by annealing with phosphosilicate glass (PSG), a process forming the quintessential device layer or field silicon, leaving the 400µm handle wafer (substrate) and its bottom-side insulating cover, the silicon oxide, intact.

The SOIMUMPs process is a simple one. First, using standard photolithography, a pattern of pad metal consisting of 20nm of chromium (used for adhesion of silicon to gold) underneath 500nm of gold is deposited by e-beam evaporation for electrical contacts and connectivity. Once the finished pad metal is protected with a photoresist layer, a "DRIE" (Dry Reactive Ion Etch) etch of silicon is done to define the device's features, often thermo-electromechanical in nature. The top layer is then completely covered in oxide while a trench is back-etched in three steps to release the device(s) above: (1) RIE removes the bottom oxide at the trench; (2) removal of the substrate using DRIE, stopping at the insulating oxide, and (3) a wet etch is used to remove the insulating oxide from the bottom side of the field silicon. Once the trench is fully formed, the protective oxide is etched from the top surface. Next, a photoresist mask is placed on the device layer so a final blanket metal consisting of 50nm of chromium and 600nm of gold can be deposited for such things as residual stress, added mass, a second matrix of connectivity or any other function a designer can imagine. Figure 1 gives cross section of the resulting structure. The piece seen hanging in air is actually attached to the rest of red MEMS layer with a tethering piece not visible at the cross section plane chosen. SOIMUMPs process details and specifications are available on line at MEMSCAP site [9].

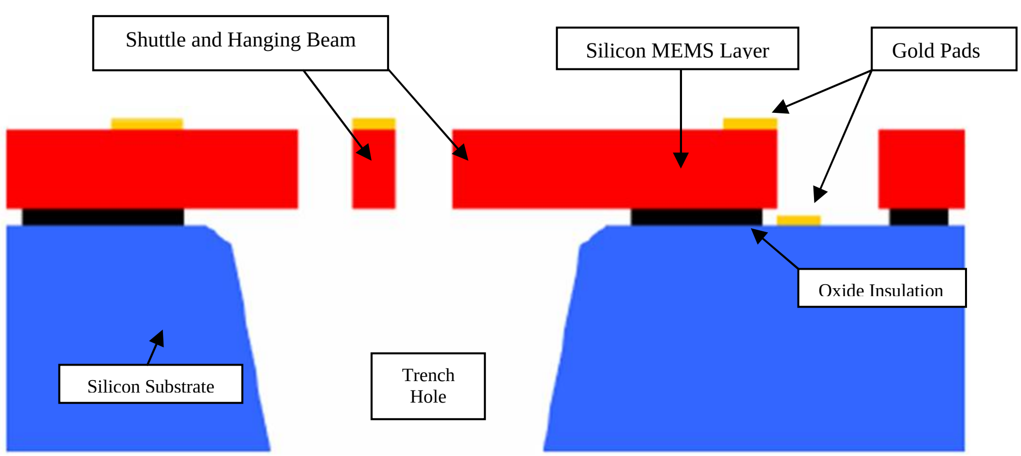

Figure 1. Cross section of a SOIMUMPs processed MEMS structure.

3. MEMS Class Design Projects

The MEMS processes mentioned above were discussed in class with some examples of sensors and the design tools were demonstrated and used in class assignments during the semester. The learning and experience gained with the tools during the semester formed the foundation for design projects assigned at the end. In the first offering, the common theme of the class projects was the design of "Acceleration Sensors" as "Impact" sensors for application in vehicle air bag deployment. Projects were individualized by assigning different impact acceleration trigger value to each student. In the second offering of the course the theme became again "Acceleration Sensors" but with a different, namely, capacitive sensor output which delivers a continuous output within a range around the acceleration value of design.

The designs had to employ the SOI (Silicon on Insulator) MEMS process, "SOI-MUMPs" available from MEMSCAP. Students were given a set of constraints such as the maximum chip area available as well as the design rules specified by the company. Designs covered a range from about 3 g's to 20 g's. ("g" is the unit of acceleration measured equivalent to Earth's acceleration of gravity, i.e. 9.81 m/s^2.)

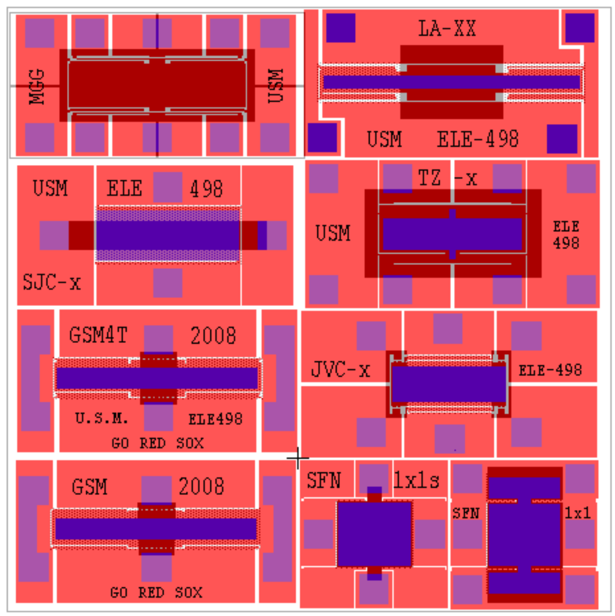

Figure 2a. A Multi-Project Chip's Design Layout which combines nine Impact Sensors students designed in ELE498 MEMS class

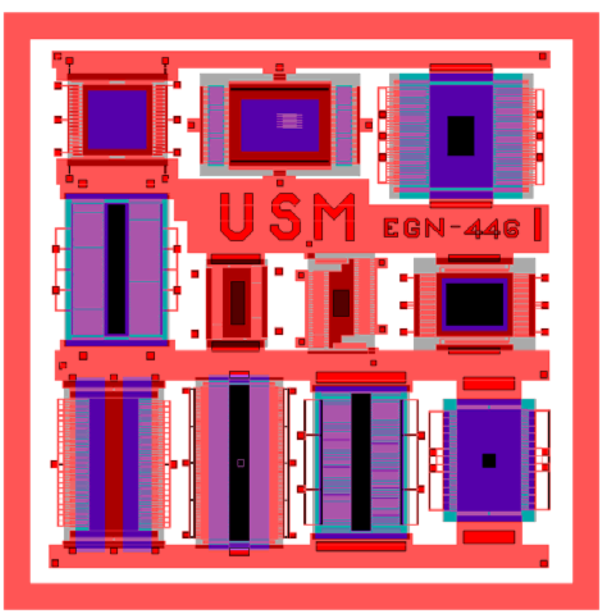

Figure 2b. A Multi-Project Chip's Design Layout which combines eleven Capacitive Acceleration Sensors students designed in ELE446 MEMS class

Figure 3 gives microphotographs of two sample student designs. The bright yellow areas are gold coated for god contacts, or to increase the shuttle mass to increase the acceleration sensitivity, or simply wire bonding pads. The serrated contact designs used in the samples which are displayed in Figure 3 are to improve the electrical contact. Shapes and sizes of the designs seen in Figures 2a, 2b and Figure 3 differ significantly from one student to another which reflects variation in individual artistic taste as well as the wide range of specifications assigned.

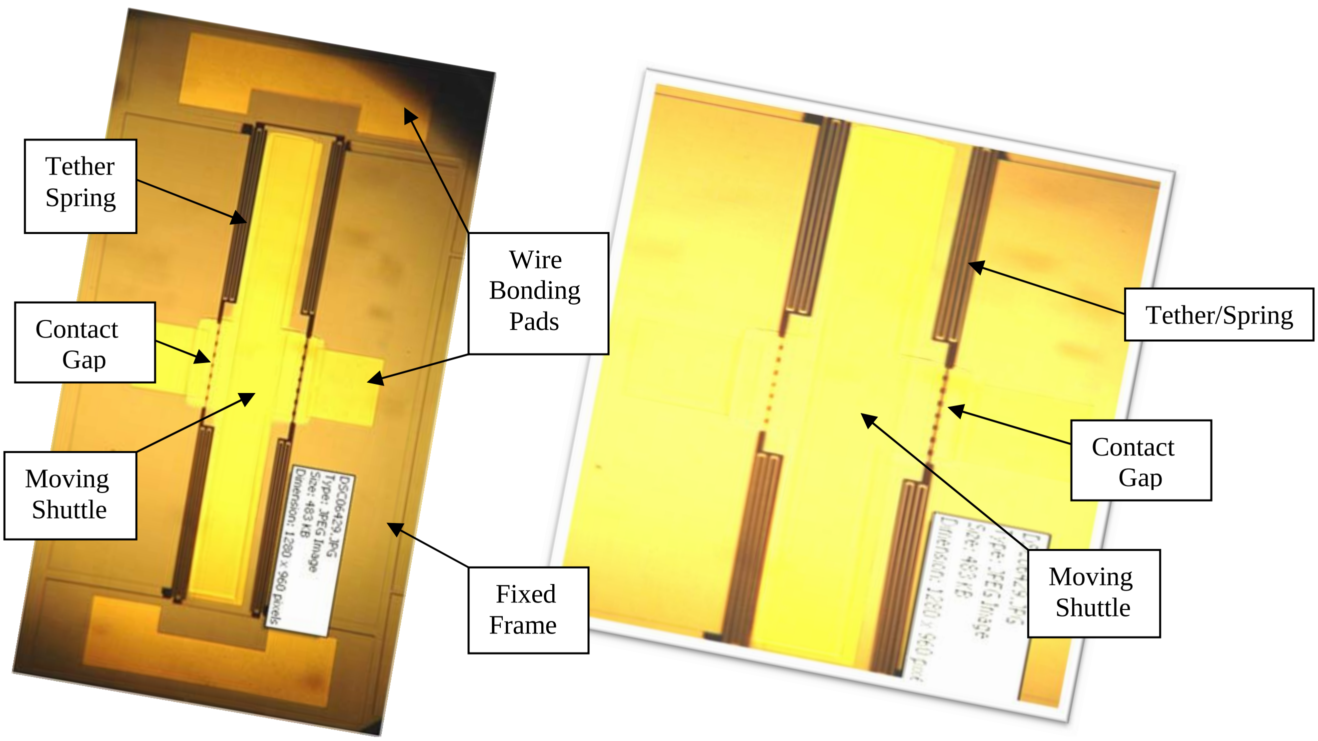

Figure 3. Two Samples of Student Designs

Thanks to the availability of funds from the instructor's NASA and MSGC grants, the student designs, after several feedback and corrections on them by the instructor to increase probability of success, were sent out for fabrication in the form of a multi-project chip which contains a total of nine such designs in year 1 (ELE 498 class) and eleven designs in year 2 (EGN 446 class). In this way the cost of fabrication could be split among all nine or eleven. Figures (2a) and (2b) give the layout of the multi-project MEMS chips formed by the instructor after merging all of the students' designs submitted. The change of the course label and number is due to official recognition of the course as a senior elective in all engineering programs (EGN) the year after the first time it was offered as an electrical engineering technical elective (ELE).

All of these designs operate based on the fact that a shuttle mass hanging in air/vacuum tethered to a fixed frame, when subjected to acceleration forces, will be displaced with respect to the frame. The displacement will be limited by the balancing force of the thin tethers acting as springs[1,2]. By forming, on the MEMS structure, electrical contacts whose gaps are calculated to make contact at the set threshold value of acceleration (or the crash point for the deployment of the air bag in a vehicle) impact sensors are created. The threshold value of acceleration the impact sensor's contacts are made is given by,

$$a_{impact} = (N_{tethers} \cdot K_{tethers} \cdot d_{gap}) / M_{shuttle} \quad (1)$$

where $N_{tethers} = 4$ is the number of tethers, $K_{tethers}$ is the spring constant of each tether, $M_{shuttle}$ is the mass of the shuttle and d_{gap} is the contact gap. Obviously, design of such an apparently simple device good sensitivity becomes challenging due to the microscopic size of the shuttle (small mass), material properties of Silicon (high Young's modulus), integrated circuit layout design rules imposed by the MEMS fabrication process and others such as the real estate area available for each design on the multi-project chip. The left hand side design shown in Figure 3 for example, has a shuttle mass of about 7 nano-grams made from a 10 µm thick rectangular Silicon piece of about 200 µm x 1400 µm dimensions. To achieve a threshold acceleration value in the order of 10 g's, the tethers had to have a very small spring coefficient, therefore they had to be very thin (2 µm, the smallest feature size allowed in SOI-MUMPs process) and the contact gaps had to be minimal (2-3 µm). That is why in Figure 2a and 2b the tethers and the gaps are hard to see. In the cross sectional structure drawn in Figure 2, red represents the 10 µm thick Silicon which is resting on a 400 µm thick Silicon substrate separated by a 1 µm insulating oxide layer.

In the capacitive acceleration sensors designed in the second year, the contacts are replaced with comb electrode[1,2] pairs whose capacitance is inversely proportional to their separation, d which varies with the displacement of the shuttle due to the force of acceleration exerted on the shuttle and balanced by the tether's opposing spring force. Therefore, acceleration is converted into capacitance through the displacement it caused in the shuttle. Unlike the impact sensors designed in the first year which had on-off contacts, determination of acceleration from the very small femtoFarad valued capacitance poses significant measurement challenges. Very sensitive differential capacitance had to be designed for use in testing these devices in addition to an accelerator to generate the acceleration forces needed for indoor tests. Such a design was accomplished as senior design projects by two students and presented at a regional conference[11].

The fabricated chips were all packaged in house by using 28-pin Ceramic DIP packages as shown in Figure 4. Wire bonding is done using a thermo-sonic wire bonder at 200 C substrate temperature with 1 mil (25 µm) diameter gold wire. Figure 4 gives a close up picture of the wire bonding of the MEMS class multi-project chip. Only after this packaging the acceleration sensors can be tested by plugging in to a proto-board placed in a metal box which is attached to the rotating arm of an accelerator (shown in Figure 5) which was also a home-built outcome of senior design projects by our students[11].

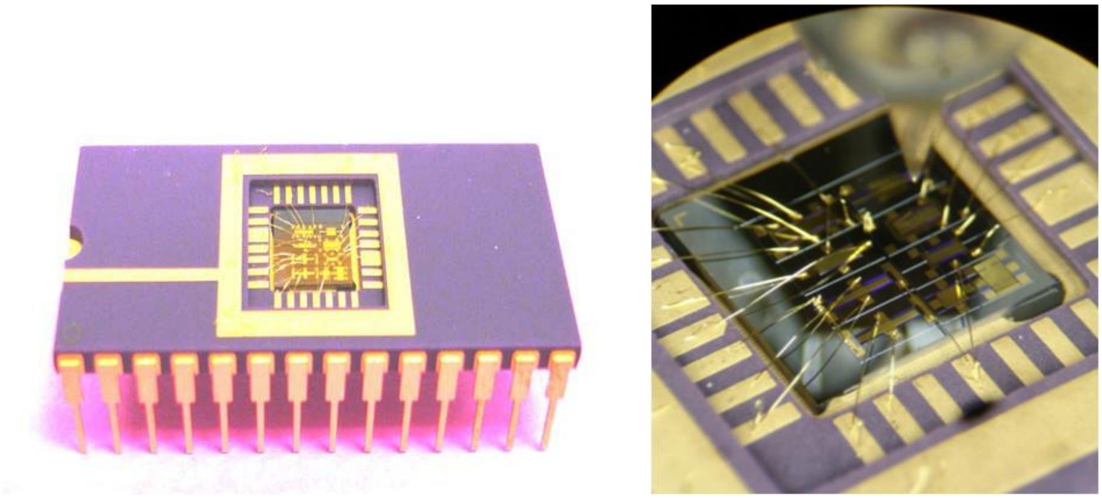

Figure 4. Wire bonding and packaging of class multi-project MEMS chip for testing

The acceleration test platform shown in Figure 5 can create centrifugal acceleration forces up to 20 g's. It consists from a 1 m long metal bar attached to a shaft at its center. The shaft is attached to a speed reducing gear and is driven by a DC motor. It can spin up to 180 rpm at maximum power, creating close to a maximum centrifugal force of about 20 g's on a test chip plugged in to the circuit boards fixed inside the metal boxes. An Analog Devices AD321XL acceleration sensor which is placed inside the test chamber along with the MEMS chip under test, acts as a reference to measure and monitor the acceleration force experienced by the MEMS chip as the speed of rotation is gradually increased to cover the acceleration test range of 0 to 20 g's. The accelerator is operated inside a transparent plexiglass shield to assure safety.

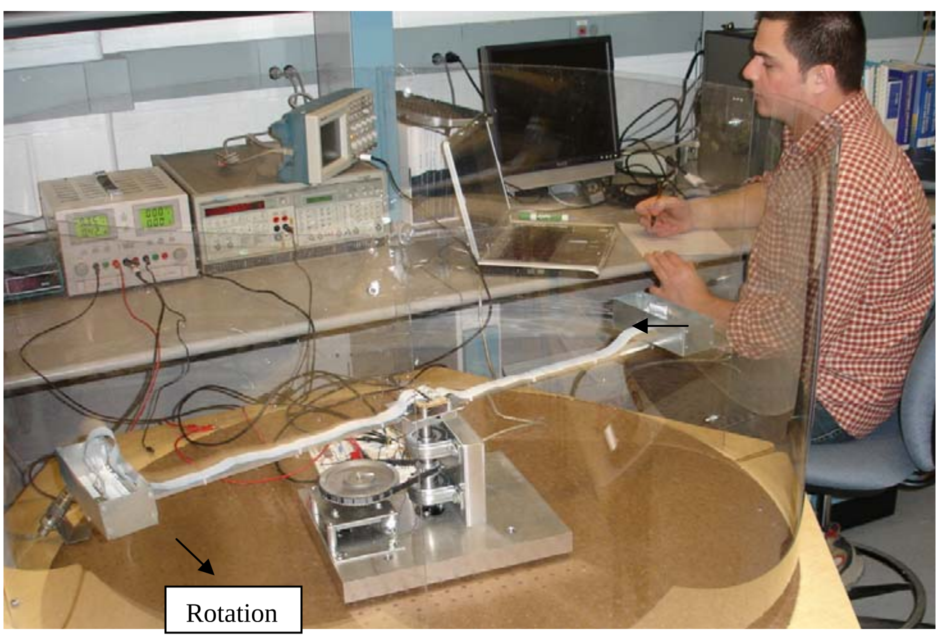

Figure 5. Acceleration Sensor Test Platform under operation

4. Results and Conclusions

Preliminary results on the acceleration tests follow the general trend of the lump model calculations using Equation (1) and the spring model and the material parameters taken from Liu [2]. However, there is typically up to 20% difference observed between the model and the experiment. The spring model is "fixed-guided beam under point loading at the free end" which predicts individual tether spring constant as $K = 12\ E.\ I / l^3$, where E is the young's modulus, l is the length of the beam and I is the moment of inertia of the beam's cross section (see references [1] and [2]). Young's modulus was taken as 160 GPa in all design calculations. Iin order to achieve small spring coefficients for high sensitivity, long and folded beams have been used. In the design calculations which are based on the lumped model it was assumed the effects of joints and end points were negligible, and the spring constant is simply divided by the number of the folded sections. Assuming isotropic material properties (constant Young's modulus) and perfectly rectangular and uniform cross section for the beams, the spring constant can be written as,

$$K_{tether} = E.\ t\ (w/l)^3 / n_{folding} \qquad (2)$$

, where t is the thickness, w is the width, l is the length of each section of the beam, and $n_{folding}$ is the number of times the beam is folded. When combined with equation (1), the threshold impact acceleration of equation (1) can be written as,

$$a_{impact} = N_{tethers}\,(E.\ t\ (w/l)^3 / n_{folding}\ ).\ d_{gap}\ / M_{shuttle} \qquad (3)$$

This is the model equation used in our design calculations. It is to be noted that, the lithography and etching control and the uniformity limit of 0.1 um of process, with typical w and d_{gap} values used in our designs (about 2 µ minimum allowed values for width and separation) amounts to 5% uncertainty in each. Total contribution of these two on the impact acceleration number of equation (3) can be as much as $(1.05)^4 - 1 = 21\%$ uncertainty. This alone explains the deviation of the actual results from our calculated values.

In conclusion, inclusion of this full cycle design experience, the testing of the fabricated chips and the finite element modeling work initiated with the second generation of the students in our MEMS class gave our students an extraordinary engineering experience, made the course popular and has almost doubled the enrollment in class, and attracted students from mechanical engineering seniors (about 25% of the class). Currently (Spring 2011), in the third offering of the course, the class has composition is 20% mechanical and 80 % electrical with all students enthusiastically learning the use of layout design tools to start their project work.

Acknowledgements

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Greg Mitchell and Steve Coleman who also helped to design and construct the acceleration sensor testing platform.

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