Sensors and Actuators Designed and Fabricated in a Micro-Electro-Mechanical-Systems (MEMS) Course Using Standard MEMS Processes

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Abstract

Use of "MUMPs" (Multi-User-MEMS-Processes) is being described 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, as term projects, various MEMS sensors and actuators using integrated circuit layout design tools and standard Silicon MEMS technologies available and known as "MUMPs". Initially "SOI-MUMPs" was chosen for the final class projects to design crash sensors and capacitive acceleration sensors. In the latest offering of the course a newer technology, "Piezo-MUMPs" was adopted for its additional piezo-electric film which facilitated MEMS designs to incorporate acoustic and vibration sensors, vibrational energy harvesting devices, piezoelectric drives, micro-resonators as well as higher temperature micro-heaters, thermal actuators and thermocouples. Successfully completed student designs were combined to form a multi-project MEMS chip and fabricated thanks to funding received from NASA/MSGC and USM. The paper presents examples of such designs including simulation and test results and test set ups/equipment.

Keywords

MEMS, PiezoMUMPs, sensors, actuators, design projects

Introduction and Background

"MEMS" which is an acronym for "Micro-Electro-Mechanical-Systems" 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 design tools and the design experience to his students, the innovators and entrepreneurs of the next decade, in addition to delivering the basic knowledge of MEMS.

Thanks to funding received from Maine Space Grant Consortium (NASA) and USM such tools and design experience could be provided in the MEMS courses offered, and more, student designs could be sent out for fabrication, packaged and tested.

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. In the paper examples of student designs, their simulation and test results are given.

"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. "MEMS Pro" has 3D visualization and can be linked to CAD and 3D finite element simulation tools such as ANSYS and COMSOL for multi-physics simulations.

"MUMPs" incorporates four main standardized MEMS processes, (1) "PolyMUMPs", a three-layer polysilicon surface micromachining process, (2) "MetalMUMPs", an electroplated nickel process; (3) "SOIMUMPs", a Silicon-on-Insulator bulk micromachining process with through the wafer holes, and (4) PiezoMUMPs" an enhanced version of SOIMUMPs with a piezoelectric layer. In our MEMS classes "PolyMUMPs", "SOIMUMPs" and "PiezoMUMPs" processes are emphasized, all Silicon based and 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. 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. Details of the process and specifications are given by Wilcenski. [8]

In most of our class design projects we employed the SOIMUMPs MEMS fabrication process for its simplicity, robust structure and immunity to "stiction", the electrostatic bonding of the thin layers in the PolyMUMPs processed MEMS devices after release etch. 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].

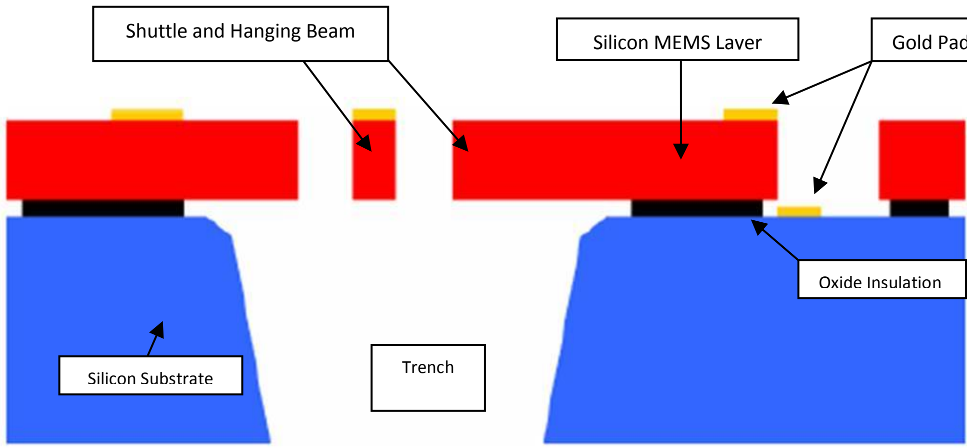

Figure 1. Cross section of a SOIMUMPs processed MEMS structure [9].

The PiezoMUMPs process is essentially the same as the SOIMUMPs process with the addition of a piezoelectric Aluminum Nitride (AlN) film deposited on the surface of the SOI layer after growing an insulating SiO2 layer. It employs Aluminum as conductor metal instead of Gold. The AlN film which is sandwiched between Aluminum on top and Silicon at the bottom, when a voltage is applied in between the two, bends upwards, creating a vertical motion. Reversal of the action produces electricity, a means to make vibration energy harvesting MEMS devices.

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. Figure 2a shows the combined multi-project chip sent out for fabrication containing 9 different student designs. Figure 3 displays the microscope photograph (on the left) of one of those on the fabricated multi-project chip.

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 the design. Figure 2b gives the multi-project chip design combining 11 individual student projects. 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 3 displays the microscope photograph (on the right) of one of those on the fabricated multi-project chip. An in-house accelerator and LabView automated test set-up was built to test these acceleration sensors.

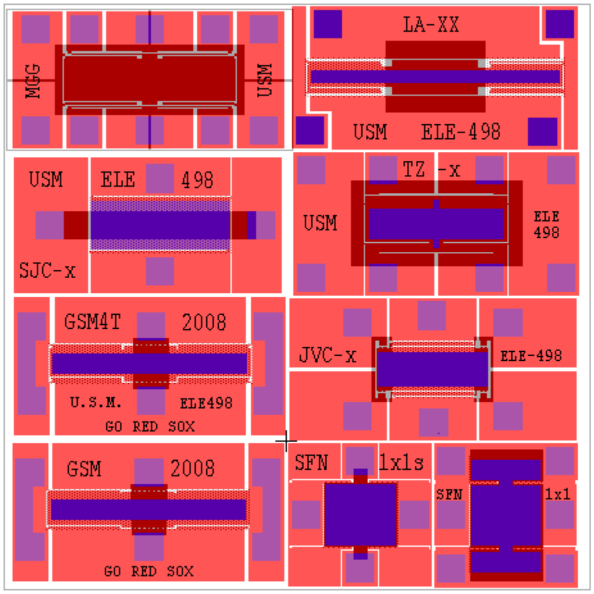

Figure 2a. A Multi-Project Chip's Design Layout which combines nine Impact Sensors students designed in ELE498 MEMS class

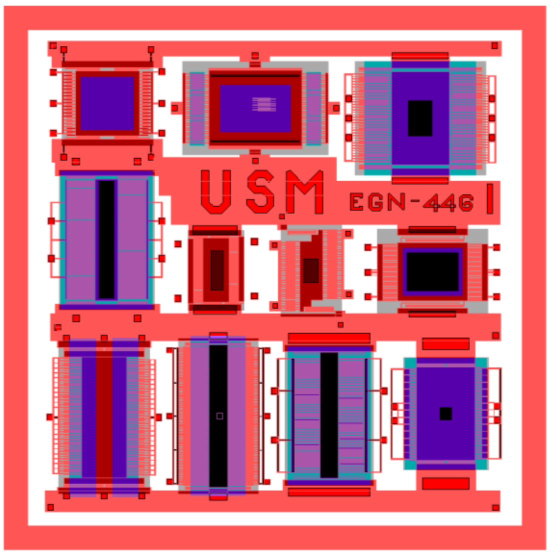

Figure 2b. A Multi-Project Chip's Design Layout which combines eleven Capacitive Acceleration Sensors students designed in ELE446 MEMS class

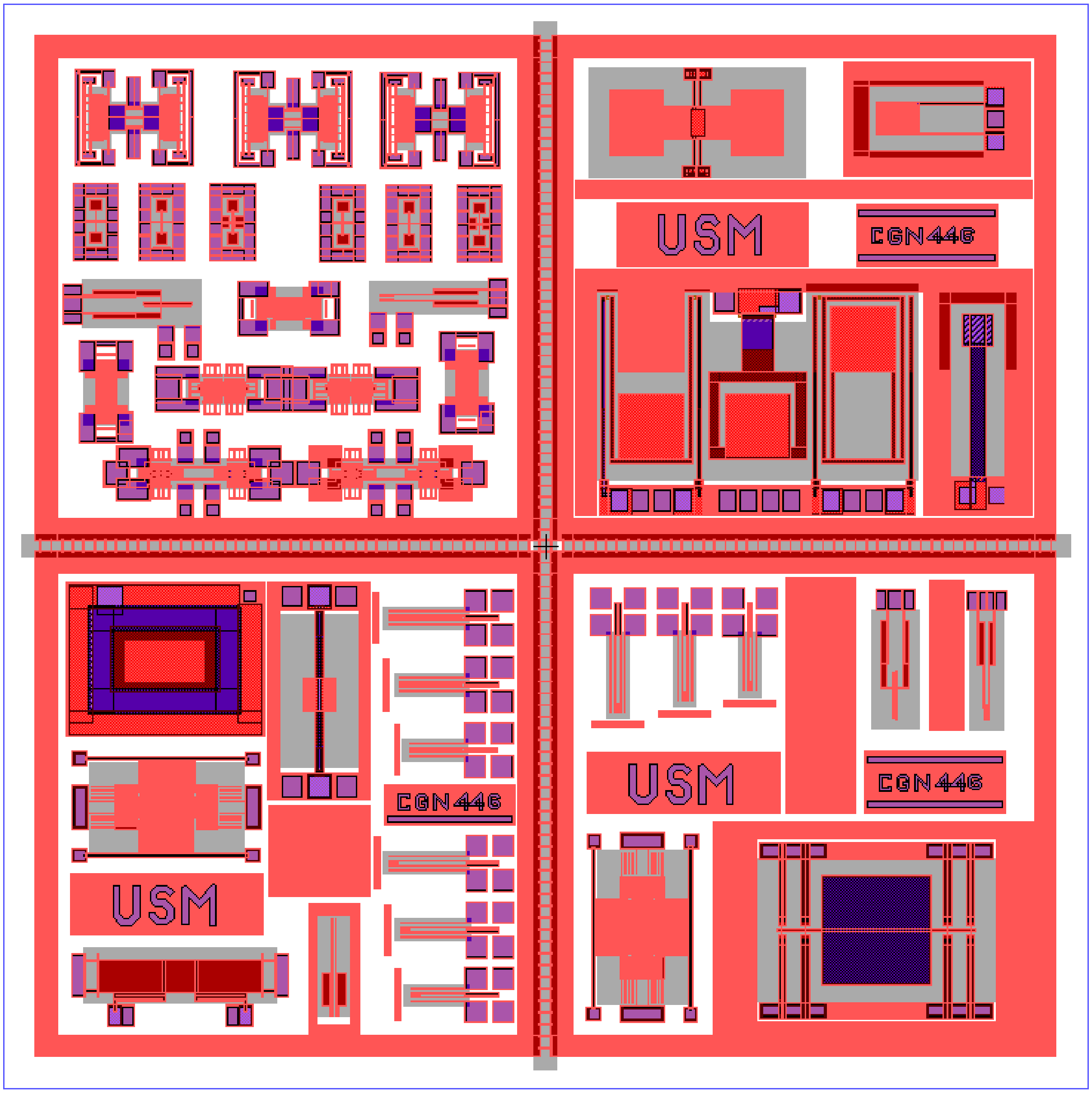

Figure 2c. A Multi-Project Chip's Design Layout which combines variations of twenty one student projects based on the PiezoMUMPs process designed in ELE446 MEMS class.

In the latest offering of the course PiezoMUMPs process was adopted as the process of the class projects. This expanded the spectrum of sensors and actuators that could be included in the projects. Rather than picking a common topic like capacitive output acceleration sensors for all of the class, as was done in the past, students were allowed to form teams up to two and allowed to pick any project that could be implemented in this technology as long as it did not require more area on the chip than the allocation permitted to fit all on one multi-project chip of 1 cm by 1cm maximum size. Figure 2c shows this multi-project chip's layout. It contains a variety of designs including vibration energy harvesters, vibration sensors, micro-heaters, thermally and piezoelectrically actuated devices, acceleration sensors, micro-grippers, resonators, etc. Because of limited space individual projects cannot not be described because of the page limits of this publication. In the conference presentation slides detailing the designs including micrographs and video clips of moving parts will be shown.

Figure 3 gives microphotographs of two samples of student designs. The bright yellow areas are gold coated for good 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, 2c and Figure 3 differ significantly from one student to another which reflects the wide range of specifications assigned to individuals.

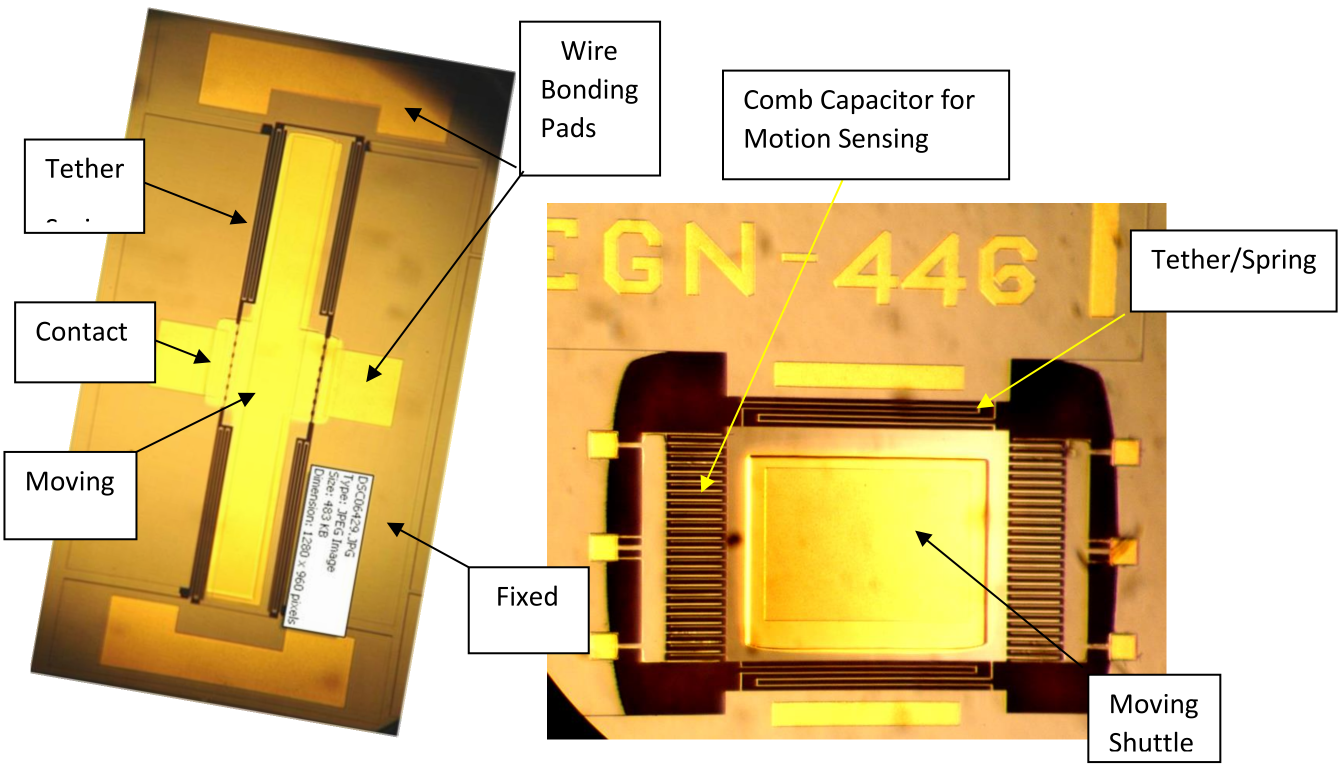

Figure 3. Two Samples of Student Designs, Impact Sensor (left), Capacitive Output Acceleration Sensor (right)

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 measurement system had to be designed for use in testing these devices in addition to building an accelerator to generate the acceleration forces needed for indoor tests. Design and construction of such an acceleration sensor test platform was accomplished as senior design projects by two students and presented at a regional conference [11], and received "Best Paper" awards.

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).

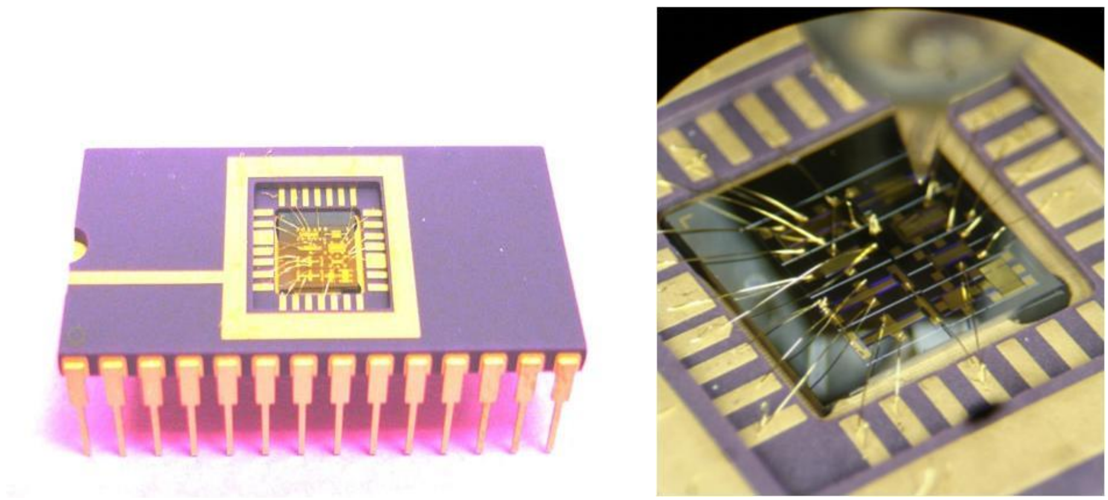

Figure 4. Wire bonding and packaging of class multi-project MEMS chip for testing

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. 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.

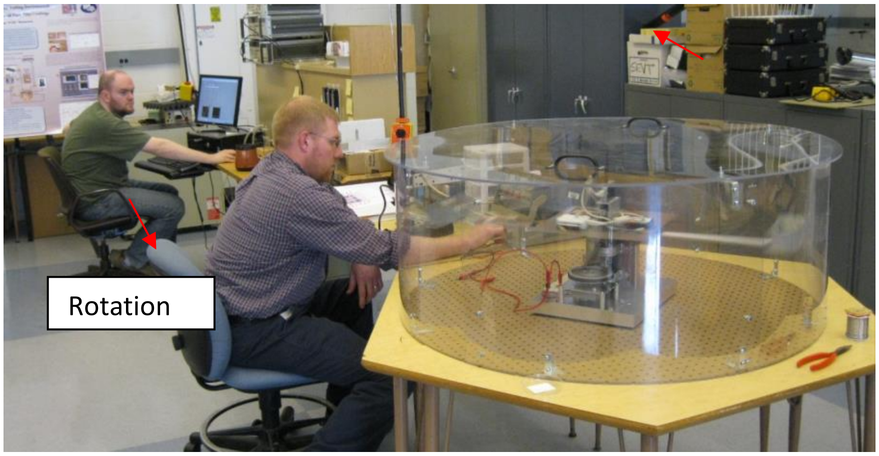

Figure 5. Acceleration Sensor Test Platform under operation

Results and Conclusions

Acceleration sensors designed were tested using the home-developed LabView controlled test set up in Figure 5. The measurement of sub-picofarad capacitances and femtofarad variations on them to extract acceleration from a sample in a rotating box were challenging but overcome. A comparison of our capacitive output acceleration sensors and a commercial acceleration sensor housed in the same test box revealed good correlation as shown in Figure 6 below. However individual calibration of each sensor had to be done because of the parasitic capacitances introduced in the test set up and the lump models used in design calculation. Results on the acceleration tests follow the general trend of the lump model calculations and the spring model and material parameters taken from Liu [2].

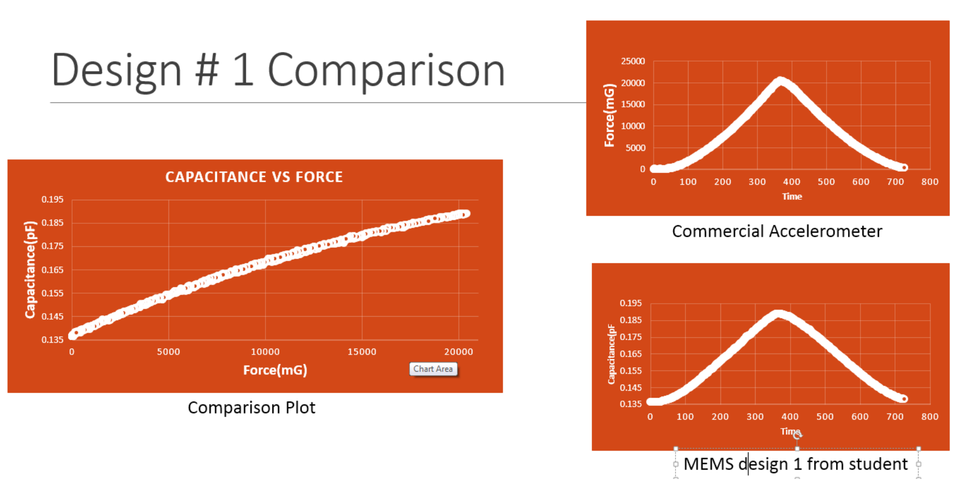

Figure 6.

The PiezoMUMPs designs were recently received as fabricated from the fab. Vibration testing set ups are being completed to test the vibration energy harvesters and vibration sensors.

Thermally actuated MEMS designs like micro-grippers have been tested to function. Work is continuing to correlate resonator designs' experimental findings with COMSOL Multiphysics finite element simulations. Three students from the MEMS class wanted to do more and are doing their senior designs projects in MEMS.

In conclusion, inclusion of this full cycle design experience, the testing of the fabricated chips and the finite element modeling work initiated in and around 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. In the last offering of the course, the class had a composition reaching 40% mechanical and 60 % electrical.

Acknowledgements

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References

1. T.H. Hsu, " MEMS & Microsystems: Design, Manufacture and Nanoscale Engineering" (2nd edition) John Wiley 2008.
2. C. Liu, "Foundations of MEMS" Prentice Hall 2005.
3. R.C. Jaeger, "Intr. to Microelectronic Fabrication, 2nd ed." Addison Wesley 2002.
4. J.P. Uyemura, "Physical Design of CMOS Integrated Circuits Using L-EDIT", PWS 1995.
5. "MEMS-ProTM" is a product of SoftMEMS, Inc. http://www.softmems.com
6. "L-EditTM" is a product of Tanner EDA, http://www.tannereda.com
7. "MUMPs" MEMS prototyping services are provided by MEMSCAP, Inc., http://www.memscapinc.com/
8. S. Wilcenski, "Introduction to Prototyping Using PolyMUMPS," available for downloading at http://www.memscap.com/en_mumps.html
9. http://www.memscap.com/en_mumps.html
10. http://www.mems.sandia.gov/tech-info/summit-v.html
11. Carlson, D, Schell, M.. and Guvench, M.G., "Development of a Rotational Accelerator Test Platform to Enable Wireless Transmission of Data and Automated Speed of Rotation " ASEE North East Conference, UMass Lowell, 2012

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