ASEE'S VIRTUAL CONFERENCE
At Home with Engineering Education
JUNE 22 - 26, 2020 #ASEEVC
Paper ID #29785

An Undergraduate Hands-On Approach to Microfabrication Applied Learning Towards Developing a Silicon-Based Microfluidic Pressure Sensor Array

Mr. Alexander Bryan Bailey, Alfred State College

I currently am a senior undergraduate student studying Mechanical Engineering Technology at SUNY Alfred State. I was a self-taught, homeschooled student before entering college, and I have now been engaged as an intern for a local manufacturing automation company for the past two years (2018-2019). When not directly pursuing academic interests, my hands turn to building drones and experimental model aircraft.

Mr. Trevor S Michelson, SUNY Alfred State College
Prof. Reza Rashidi, State University of New York, Alfred State

Reza Rashidi is an Assistant Professor in Mechanical Engineering Technology and a faculty affiliate in Micro/Nano Fabrication Laboratory at State University of New York, Alfred State College. He received his Ph.D degree in Mechanical Engineering (MEMS development) from the University of British Columbia in 2010 and completed his Postdoctoral Fellowship in Development of Biomedical Sensing Devices in the Department of Electrical and Computer Engineering at the University of British Columbia in 2011. He also received a minor degree in Engineering Management and Entrepreneurship from the University of British Columbia in 2009. He has over 18 years of industrial experience. Before joining Alfred State, Dr. Rashidi was a Senior Engineer at Siemens, where he worked on research projects from 2011 to 2016. His expertise is in the development of micro/nano sensors and actuators in Biomedical Engineering and Energy applications. Dr. Rashidi was a recipient of several awards including the 2008 British Columbia Innovation award, administered by BC province, Canada. He has written over 30 research articles and is currently a reviewer of several journals and conferences worldwide.

An Undergraduate Hands-On Approach to Microfabrication Applied Learning Towards Developing a Silicon-Based Microfluidic Pressure Sensor Array

Alexander Bailey, Trevor Michelson and Reza Rashidi
Department of Mechanical and Electrical Engineering Technology, Alfred State College,
State University of New York, Alfred, NY 14802

Abstract

This paper presents an accelerated applied learning approach for fabrication of a MEMS (MicroElectroMechanical Systems) 5x5 pressure sensor array by an undergraduate student. A potential application of this device would be in microfluidic lab-on-a-chip devices where pressure sensing is required at various locations of the microfluidic channels. The microfabrication processes required for producing such devices usually require essential knowledge in different areas of mechanical, electrical and chemical engineering, and these skills may not be possible to be achieved with traditional learning cycles. In addition, these emerging processes are usually taught to graduate students who have already mastered the fundamentals of engineering. In this research, the instructor of the course designed an accelerated approach to get the undergraduate student up to speed in this field in a short amount of time. The idea behind this research was to find the most efficient way of microfabrication learning within an academic semester rather than developing a device. The mechanical engineering undergraduate student received help from two resources. First, the instructor of the course, who helped the student in the device ideation, design, fabrication process flow, and other areas where needed. Second, the lab assistant, a senior student with hands-on microfabrication course experience who provided the undergraduate student with help in fabricating the device in the clean room. The undergraduate student compiled his experiences as a portion of discussion for the applied learning results. The effectiveness of the proposed teaching method was assessed by various resources, including undergraduate student assessment, lab assistant assessment considered as a peer review, and instructor self-evaluation. In addition, the results of the microfabrication was separately assessed and considered as the major assessment of teaching effectiveness. The device was evaluated for its reliability using an optical microscope and showed that the major design configurations were successfully fabricated. This hands-on approach was found to be an efficient accelerated learning cycle when an undergraduate student is required to gain knowledge in certain nontraditional areas.

Introduction

Microsystem Technology

MEMS (Micro-Electro-Mechanical Systems) technology has seen remarkable growth over last two decades. The first micromachined silicon-based pressure sensor was demonstrated in 1970. Since then, significant improvements have been made to the design and fabrication of these devices through their layouts, materials, and processes. Even today, among several existing technologies, only microsystems can support producing small, intelligent, robust, multifunctional, and low-cost devices. Examples of MEMS devices are pressure sensors, inertial measurement unites (IMU), microphones, micro speakers, micro mirrors, switches, etc. Because MEMS integrate microelectronic and mechanical components on a single chip, they have been used in many applications such as biomedical [1], defense [2], aerospace [3], automotive [4], power [5], etc., and the need for such devices is rapidly growing. In addition, the number of companies producing such products are growing due to increasing demand from consumers and other industries.

Some of the same microfabrication techniques used in integrated circuits (IC) are utilized to fabricate MEMS devices. These devices usually include moving parts that do not exist in IC designs. The moving components allow for sensing or actuating functions within the MEMS devices. Additional processes such as wafer-level bonding [6], surface micromachining [7], and bulk micromachining including wet or dry etching of silicon [8] are required to complete the cycle of MEMS fabrication. These techniques allow for creating components such as cavities, membranes, channels, reservoirs, nuzzles, etc. [9] which can be used in microfluidic devices.

Microfluidic devices were demonstrated as ink jet printing nozzle arrays in early stage of MEMS development [10]. Initially established as a method of shrinking down total chemical analysis systems (µTAS), the field of microfluidics has brought new possibilities to applications where fluids are transferred, mixed, and analyzed. The interest in using these devices has been significantly increased in past two decades. The technology utilizes the same fabrication techniques and materials as MEMS but differs in that the primary features of the design are comprised of micro channels laced with various mechanical and electrical elements [11]. Many of the recently developed microfluidic devices include various components such as microvalves, micropumps, and reservoirs ideal for different applications [12]. Upon increasing the demand for biomedical devices, microfluidic systems have attracted more attention. As a result, microfluidic devices have expanded to include more features such as filters, mixers, separators, etc. In addition, they are required to have more sensing functions within a single chip [13]. They have been used in several applications such as drug delivery [14], lab-on-a-chip [15], fuel cell [16], etc. Microfluidic transdermal drug delivery seeks to transmit chemical compounds into the body’s circulatory system for controlled delivery. Such a system would use microneedles integrated with micropumps to accomplish the delivery of the fluid [17]. Lab-on-a-chip technology utilizes previously mentioned MEMS components and microfluid physics (capillary action and such phenomenon) to conduct tests and treatments to small (drop sized in some cases) samples of fluid in a compact package. Examples of these applications can be seen in handheld blood cytometers and insulin testing devices [18]. The market for microfluidic devices is estimated to be several billion dollars. In addition, there is a shortage in skilled labor in microfabrication field. Therefore, preparing special programs to train engineers for this area seems to be necessary.

The construction of micro devices, particularly pressure sensors, with MEMS fabrication techniques has been a developing practice for the past couple of decades. A major process used in this fabrication is wet anisotropic etching, the most preferred one in industry due to its effectiveness and cost. This process utilizes a chemical solution such as tetramethylammonium hydroxide solutions (TMAH) to bulk etch silicon. The technique works best for rectangle features parallel to the crystal grains on the wafer [19]. Though not well suited for convex corners or rounded geometries due to the rapid undercutting rates present in such configurations, compensation structures and specialized TMAH solutions are used to realize unconventional designs [20]. Since the mid-1990s, MEMS sensor features have been etched onto silicon wafers using a lithography technique with ultraviolet (UV) light and light sensitive photoresist in conjunction with photomasks. The precision in this process requires a clean room facility with dedicated microfabrication equipment such as wet benches, mask aligners, evaporators, etc. [21].

The idea of arranging pressure sensors in a linear array or a square matrix is not a strictly unexplored venue. The inspiration for this design comes from observations of blind cave fish that possess the ability to navigate dark and murky waters using a natural lateral line of pressure differential sensors that provide high speed obstacle avoidance despite the lack of light detecting eyes [22]. By adapting this natural mechanism in a MEMS format with an array of pressure sensors, a system for passive environment detection, navigation, and efficient mobility (detection of self-created underwater vortexes to avoid) without sonar or other electromagnetic wave dependent devices is possible [23]. Other explored applications for such technology have been found in the robotics industry with the fabrication and study of tactile image sensors, or an array of pressure sensors on the surface of a robotic finger (artificial skin) intended for physical contact with objects. The pressure senor array allows for the evaluation of distributed contact pressures when touching or potential handling of objects, providing data for precise application of forces or object feature recognition [24].

Applied Learning

Since the early 2000's, the demand for engineering students with MEMS training and experience has risen dramatically due to the lack of undergraduate MEMS programs available and the exploding growth of the MEMS industry. Several universities and other academic institutions have risen to this call of educating the engineering undergraduate students with the formation of homebrewed MEMS courses, practical hands-on laboratory experiences, and simulation software [25]. The consensus for the lecture content of these MEMS programs revolve around a "crash course" style format due to the numerous parts of widely varying engineering disciplines involved in the MEMS field. Students will come face to face with principles and content originating from mechanical, material, electrical, and chemical engineering used in the context of MEMS design, fabrication, and testing. These topics will never be totally covered by the average undergraduate's previous course work, so the student must be prepared to exercise flexibility when studying these "back-fill" subjects [26]. Finally, if nothing else, the MEMS course must consist of a heavy "hands-on" laboratory environment that provides students with basic clean room skills and etiquette such as gowning and MEMS fabrication techniques including wafer oxidation, creation of photolithography masks, chemical etching, anodic bonding and more. In mastering these processes, the students shall become proficient with laboratory equipment such as oxidation furnaces, mask aligners, and sputtering systems [27]. In order to develop MEMS devices, Mechanical Engineering students may need to acquire knowledge on electrical and mechanical functions as well as microfabrication processes. As there is no such a program to provide a combination of these experiences, custom programs are required to develop this knowledge in motivated students. Like traditional programs, the custom programs may include various types of courses designed to support the program objectives.

There are several conventional methods used to measure the teaching effectiveness of the courses within the academic programs. The measurements are used for decisions on the future of academe, including formative decisions used to improve the teaching quality and summative decisions employed to determine faculty promotion and pay [28]. There are standard ways of measuring teaching effectiveness, called Standards for Educational and Psychological Testing, and they determine how and what should be measured [29]. In these standards, there are many evidences used to be measured. Some of the evidences such as student assessments have traditionally dominated [30] while there are few recent measures that can reinforce the teaching effectiveness assessment. These evidences may include faculty peer review, faculty self-evaluation, student surveys, learning outcome surveys, teaching scholarship, teaching awards, teaching portfolio, and surveys of exit alumni, employers and administrators [28], [31]-[33].

This paper presents applied learning methods used to help undergraduate students learn microfabrication techniques, particularly those used for fabricating a microfluidic device containing an array of pressure sensors. A few applied learning projects have been performed using a similar method proposed in this paper [34]-[37]. The sensors have the potential to measure pressures at different locations of the microfluidic channels. The MEMS device fabricated in this paper is a culmination of all the above topics introduced. It includes major components of pressure sensors that may be used in microfluidic devices later. The five by five pressure sensor array will be towards a demonstration of a Lab-on-a-Chip prototype and is constructed with MEMS fabrication techniques in an undergraduate level MEMS class by an engineering student with no previous MEMS or clean room experience. Details of design and fabrication processes used in this activity is described. In addition, the applied learning methods utilized in the research are discussed.

Design

The five by five pressure sensor array was designed in SolidWorks utilizing the software's configuration settings and parametric equations to create four versions of the MEMS device with different dimension combinations for the groups of diaphragm membranes, piezoresistors, and aluminum traces to the wire pads. The four configurations were covering a range of designs including 1.1, 2.1, 3.1 and 4.1 in order from least likely to most likely to succeed based on clean room capabilities. The dimensions for the configurations are presented in Table 1. The individual pressure sensors are of the typical MEMS membrane design, featuring etched cavities on one side of the wafer bounded by a thin silicon membrane and an anodic bonded glass cover as shown in Figure 1.

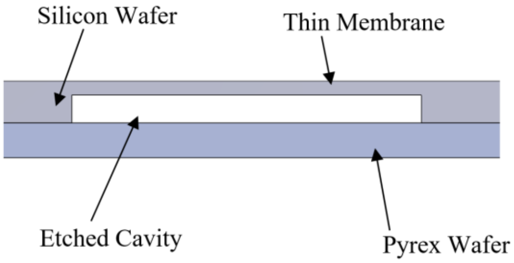
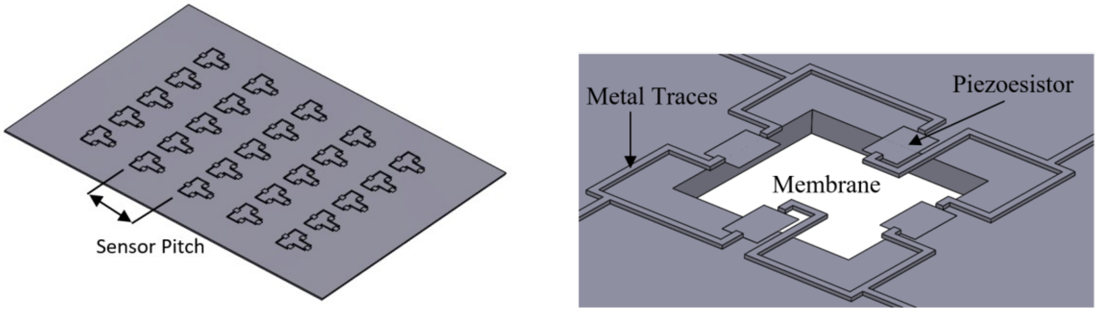


Figure 1: Cross-sectional view of a pressure sensor design.

As the driving factors in designing this MEMS device were a delicate balance between clean room capabilities vs. form factor, certain aspects of the sensor array were derived from SolidWorks simulations of the fully constructed device. A prime example of this is the individual pressure sensor pitches of the array as presented in Figure 2(a). This distance was the result of inputted dimensions for the known device elements (resistor width, resistor length, diaphragm size, trace widths, and spacing between traces) and parametric equations tuned for distributing the most compact, yet manufacturable spacing of the diaphragms possible.

Figure 2(b) displays the layout of an individual pressure sensor in the array with resistors straddling the edges of the membrane (hidden) in both orientations and joined by aluminum traces as a Wheatstone Bridge circuit. When the diaphragm flexes due to the pressure differential on the membrane, the piezoresistive nature of the resistors will change the overall resistance of the Wheatstone bridge circuit in a manner that can be calibrated to the existing pressure differential. The final dimensions for the four different sensor arrays are compiled in Table 1.



(a) (b)

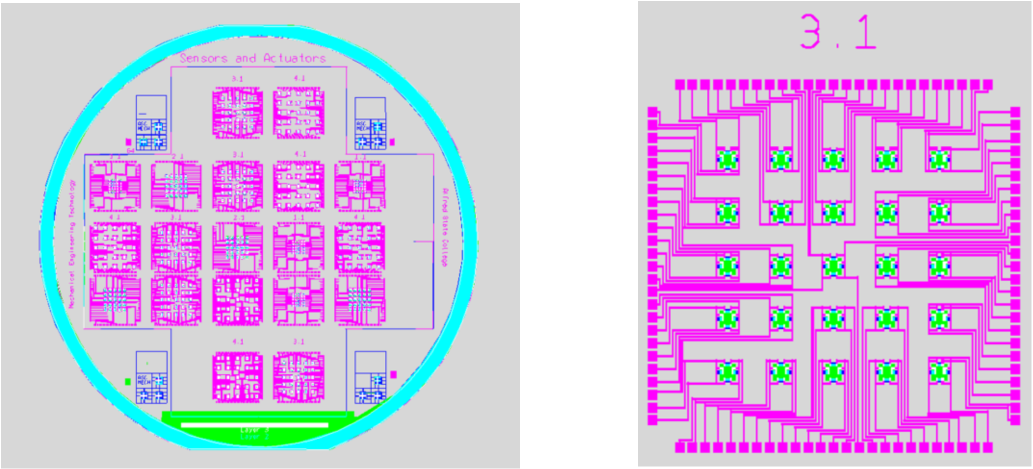
Figure 2: a) SolidWorks design of a full pressure sensor array. b) Layout of an individual pressure sensor in the array.

Table 1: Dimensions for all iterations of the pressure sensor array.

Design Case	Resistor Width (µm)	Resistor Length (µm)	Diaphragm Width (µm)	Diaphragm Pitch (µm)	Pad Width (µm)	Pad Spacing (µm)	Trace Width (µm)	Min. Trace Spacing (µm)	Chip Length (mm)	Code on Wafer
Configuration 1.1	20	30	200	660	300	100	20	20	12	1.1
Configuration 2.1	100	150	500	1110	300	100	20	30	12	2.1
Configuration 3.1	100	150	500	1650	300	100	50	50	12	3.1
Configuration 4.1	100	150	500	2190	300	100	80	80	12	4.1

Fabrication

The SolidWorks models were initially used to demonstrate various designs of the pressure sensor arrays. In order to be able to fabricate the array, masks pertaining to different layers of the sensors were formed. The designs were first drawn in the Ultiboard package which is a custom software for developing MEMS devices. The designs were then plotted onto raw film masks using a 10 µm resolution laser plotter in a dark room. The films were then developed in the same dark room. These masks were then used to fabricate the pressure sensor arrays. Figure 3 shows Ultiboard drawing of the masks on the wafer level and a close-up image of an individual array of pressure sensors on the wafer pertaining to configuration 3.1 as presented in Table 1.



(a) (b)

Figure 3: a) Ultiboard drawing of masks on the wafer level. b) Close up image of an individual array of pressure sensors on the wafer pertaining to configuration 3.1 presented in Table 1.

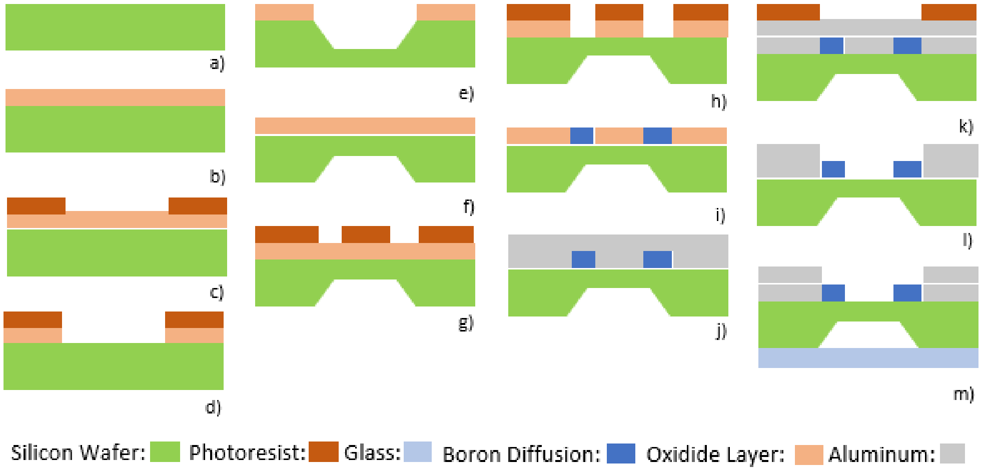


Figure 4: Fabrication process flow of the pressure sensor array including: a) RCA clean, b) thick oxide growth, c) lithography, d) oxide etch, e) silicon etch, f) oxide growth on the front side of wafer, g) lithography of the front side of the wafer, h) oxide etch, i) boron diffusion, j) deposit aluminum, k) lithography, l) etch aluminum, and m) anodic bonding of Pyrex to silicon.

The pressure sensor arrays were fabricated using traditional MEMS fabrication techniques on a 100 mm P-type silicon wafer at the Alfred State microfabrication clean room. The essential fabrication process flow is depicted in Figure 4. After performing the appropriate RCA cleanings, a 5000 Å thick oxide growth for bulk etching was generated on the wafer in the furnace. The array cavity patterns were then transferred from the first mask to the wafer surface via photolithography. The oxide was then etched to uncover the silicon surface for bulk etching and the excess photoresist from the photolithography process was stripped off. The wafer was then wet etched in TMAH to define the membranes for demonstration purposes.

The oxide was then removed, and the wafer was cleaned and prepared with the same processes as before for thick oxide growth on the front side of the wafer for the boron diffusion run. The resistor patterns on the second mask were then transferred onto the silicon wafer using the same processes above. The oxide patterns for the resistor openings were etched and the photoresist was then stripped away. After performing a piranha and RCA clean, the wafer was subjected to a diffusion furnace run to dope the boron into the openings on the oxide in order to realize the piezoresistors. The resulting oxide layer was etched thin in preparation as a thin electrical insulator. The surface of the wafer was then put through another RCA and piranha cleaning run followed by a diluted hydrofluoric acid (HF) dip to prepare for the aluminum deposit by the thermal evaporator. Faithfully following the same photolithography process for the final time, the aluminum trace patterns on third mask were marked onto the wafer. The excess aluminum was then etched, and the photoresist stripped off. Figure 5 shows the final product of the silicon wafer made by the microfabrication process.

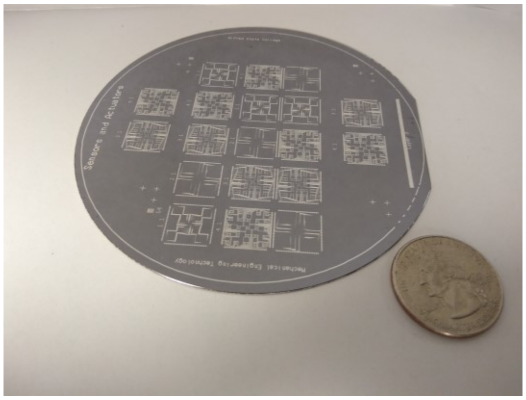


Figure 5: Fabricated pressure sensor arrays on the silicon wafer.

Results and discussion

Applied Learning Results from Student's Perspectives

This project was initiated with no prior experience other than having mastered the standard facets of a mechanical engineering degree such as chemistry principles, mechanics of materials, and circuit analysis. The motivation to participate in the applied learning microfabrication course was simply to explore the MEMS fabrication process in a relevant time window and to gain clean room experience for a potential graduate degree or a job in the MEMS field. As the lab assistant was always present to demonstrate microfabrication techniques and clean room practices, confidence was developed and maintained concerning the results of the fabricated design. Any issues with the design would be attributed to the design of the device and not the manufacturing process driven by fresh hands-on experience.

Before any microfabrication was begun, the lab assistant conducted a brief tour and introduction of the microfabrication facilities at Alfred State College. Fume hoods, wet benches wafer spinners, mask aligners, photomask printers, and furnaces were all pointed out and defined by purpose and operation for the microfabrication training process. Following clean room sessions concentrated on presenting the previously mentioned laboratory equipment in full detail. This was done by the lab assistant demonstrating the functions of each machine while fabricating an example MEMS device. The undergraduate student then was invited to repeat certain microfabrication steps such as chemical solution preparation, mask alignment and photoresist development under the lab assistant's supervision. This process provided opportunities to exercise critical lab equipment operations and steps before the experimental device fabrication. In parallel to clean room training activities, the concepts and design requirements for a silicon membrane-based pressure sensor array was presented by the course instructor. As the goal was to explore device designs with different combinations of feature dimensions for the pressure sensors, the undergraduate student resorted to using SolidWorks to develop device feature spacing. This decision was based on past mechanical engineering internships where he had participated in rapid prototyping processes utilizing SolidWorks configurations and parametric equations for product design and conception. The four configurations were designed in SolidWorks with a fluidity and rate that NI (National Instruments) Ultiboard could not rival. Once the general spacing for the etched diaphragms, boron doped resistors, and deposited aluminum pads were determined, the designs were recreated in NI Ultiboard, and the aluminum traces were included to connect the other device features. Although the student had previous experience with the NI Ultiboard software, it took approximately 15-18 hours to draw the silicon etch, boron diffusion, and aluminum disposition masks. The mask files were then exported and given to the lab assistant for printing on emulsion paper to create the device photomasks.

After completing the MEMS fabrication training with the practice wafer, the undergraduate student was prepared to construct the pressure sensor matrix. During these clean room sessions, the lab assistant was always present. His only purpose was to verbally distribute procedural instructions if needed and assist if the wafer or the device design was at risk (to retain the integrity of the project timeline). For each of the wafer cleaning processes, the student performed the wafer handling and the majority of chemical solution preparations. In several instances, the lab assistant would prepare the cleaning solutions in parallel to the student advancing the wafer process to the cleaning steps in order to save time. All furnace runs for thick oxide thermal growth and boron diffusion were conducted by the student with the lab assistant observing the run and checking the furnace controllers for correct programming. The undergraduate student performed most of the wafer handling. This portion of the microfabrication experience featured minimal hands-on work since the concern for the process was focused on the furnace programming and oxygen gas injection times. All photolithography portions of the lab were not difficult to perform, though the lab assistant did need to point out the correct order of vacuum locks again on the mask aligner. Coating both sides of the wafer with the photoresist and soft baking was dependent on already proven wafer handling skills. Beyond the previously mentioned issue with the photomask aligner operation, the entire process was mastered and unhindered each time it was required during the device fabrication. Photoresist development was one of the most challenging steps in the design mask transfer process as it was purely dependent on observation and experience. It was a tough time discerning the appropriate time to remove the wafer from the developer solution without it being underdeveloped (not enough of the UV exposed surface removed) or overdeveloped (a part of the UV non-exposed in addition to the UV exposed surface removed). However, the practice wafer provided just enough experience to accomplish this step for the experimental MEMS device wafer. The silicon oxide etch was easy to perform due to its simple nature (consistent etch rates and visual indication of the exposed silicon surface exhibiting hydrophobic characteristics). The bulk silicon etch process to define the pressure sensor membrane positions was demonstrational in nature and was conducted with fixtures that the lab assistant had previously arranged. The final microfabrication process that the lab assistant majorly assisted in was the operation of the evaporator for aluminum disposition. The lab assistant operated the evaporator under close observation for the acquisition of secondhand experience in using the device.

The applied learning MEMS clean room experience was very fruitful for the undergrad student. The opportunity to learn about and gain firsthand experience with the microfabrication processes in the Alfred State clean room in the accelerated timeline allowed for exploration of a challenging MEMS design that would ordinarily be impossible for a novice microfabrication undergraduate student to pursue. In this paper, a MEMS device was successfully designed and fabricated that boasted advanced MEMS concepts with Wheatstone bridge based silicon membrane pressure sensors and critical dimensions of 20-50 μm. Based on this experience, the undergraduate student is now capable of replicating the essential microfabrication processes to produce such a device and has gained insights for improving the current device design to comply with the real-world manufacturing capabilities of the Alfred State clean room.

As with all projects, there were some portions of the microfabrication process that were not executed as planned. The aluminum traces for device design configurations 1.1 and 2.1 were unable to be realized due to unforeseen design flaws. There was not enough spacing between the 20 μm wide traces for the photomask laser printer to properly define those elements. In addition, the traces failed due to overdeveloping in the photoresist developer solution. The configurations with smaller critical dimensions were washed away while waiting for larger features in the other configurations to develop properly. These results, although not desired, are still valuable feedback concerning the student's MEMS designs and how they might be altered for a higher fabrication success rate.

Finally, due to the student's general inexperience and accelerated timeline of the project, there were several risks involved in the MEMS device design and fabrication process. The scope for physical damage risks included the wafers during handling and the lab equipment used during the microfabrication process. These risks were necessary to retain the integrity of the applied learning purpose of the course. Unfortunately, these elements also had the potential to derail the entire project should a wafer be accidentally destroyed or a piece of lab equipment be damaged during use. The physical damage in each of these situations would translate to a time risk that would have to be accounted for. Two wafers were sent through each microfabrication step together as a measure of redundancy to keep the project on time in a defensive manner in the case of breaking one of the wafers. In the case of lab equipment destruction, only the evaporator unit utilized for aluminum disposition was deemed too sensitive to be operated (during the risk assessment for the microfabrication process) by the student for the experimental device design, and therefore it was operated solely by the lab assistant with close observation by the undergraduate student as the best alternative. All other portions of the microfabrication process were considered safe enough for the undergrad student to handle.

Applied Learning Results from Instructors' Perspectives

The undergraduate student for this course was chosen based on merit. He was within the top five students in the program. This senior student particularly performed very well in Mechanics of Materials course instructed by the same professor in junior year. In addition, the student had shown great hands-on skills as well as analytical capabilities. Furthermore, the selected student had taken prerequisite courses such as chemical principals. He was not instructed with the typical "crash course" barrage of MEMS fabrication theory, micro machining equations, and review of existing MEMS device design before entering the lab.

In order to develop essential microfabrication skills in the student, the instructor of the course initiated a hands-on project where the undergraduate student got helped from two resources, the instructor and the lab assistant, to gain essential skills in a short amount of time. This time is usually dictated by industry as there is a shortage of such engineers while the technology is growing with a fast pace. The instructor provided the student with a project subject with a minimal prerequisite to start. The idea of pressure sensor array with a potential use in microfluidic devices was one of the topics that the student could quickly begin to work with. This was a crucial step as providing an idea with a difficult concept was hard to be understood by him. The student began with a short literature review on the subject to get familiar with the theory behind the idea. The instructor then helped the student to design the device in more detail and provided him with a microfabrication process flow. The instructor provided the student with four configurations with different critical dimensions, from least likely to most likely to succeed. The student was not expected to develop all four configurations as the first two ones (1.1 and 2.1) contained features that requires years of experience and great equipment to be made. However, the instructor made a clear criterion that the student would be able to pass the course with a high grade if the last two configurations (3.1 and 4.1) were properly developed by the student. It was then upon the student to draw the design in SolidWorks and create the mask drawings in Ultiboard software package.

The undergraduate student learned essential microfabrication techniques and processes used in developing the pressure sensor array in this paper by an apprentice style laboratory experience. This was done with the help of the lab assistant who was a senior student and had passed the hands-on Microfabrication Technology course (Alfred State, MECH 7403) prior to fabricating sample MEMS devices. The instructor provided the student with a chemical safety manual. The student self-studied the manual and completed a safety test online required for anyone who was going to use the clean room facilities. In addition, the instructor prepared the fabrication process flow and detailed step-by-step instructions on the fabrication processes. The students reviewed and followed the instructions along with the hands-on help from the lab assistant during the fabrication process. The student was able to practice established microfabrication techniques, gain familiarity with the lab equipment and become experienced in working with the various acids and other hazardous materials required to fabricate the prototype device without endangering it. For the RCA clean and other such dipping procedures, the lab assistant would demonstrate procedures for mixing cleaning solutions, heating the solutions for the cleaning process, placing the wafers into the solution, removing the wafers from the solution, rinsing the wafers with deionized water, and spin drying the wafer. The student then performed the same steps under the lab assistant's supervision till confident in his abilities to conduct the processes for the sensor array. This teaching practice was then repeated for the rest of the required MEMS fabrication steps. The student was assisted by the lab assistant in programing the lab furnaces for thick oxide growth and boron diffusion runs. He also gained experience handling wafers with the glass fixtures used for furnace operations. Photoresist spinning was an easy process for the student to understand, although it took a little practice to deposit the correct amount of photoresist onto the wafer for optimal patterning results. The mask aligner in photolithography process was the second most difficult machine for him to master. The lab assistant had to demonstrate the machine's operation several times regarding the numerous valves, ball locks, and pumps that needed to be off, flipped, or on for the best mask alignment and imprinting on the wafer. The student had to make several attempts at the lithography process before he was able to land a consistent mask alignment as proven by the profilometer. The next step of the MEMS fabrication was to use the thermal evaporator for aluminum deposition on the silicon wafer. This step was the steepest learning curve as the process provided no room for error. The aluminum film deposition could be easily ruined by any small mistakes. The student prepared the wafers for the deposition process and was able to participate in the machine's operation by following its standard operating procedure (SOP). As this machine was only used once in the microfabrication process, it was treated with the most delicacy for its final operation.

When the undergraduate student was ready to fabricate the pressure sensor array on the wafers, he was confident in his ability to effectively perform the required manufacturing processes. This left the student free to focus on determining what components of the clean room used in the MEMS fabrication might hinder or define the critical features on the sensor array, as opposed to human error. After the devices were constructed, each configuration of the sensor array was tested and inspected for trace integrity and feature spacing which hold the potential to produce testbeds for future fully functioning pressure sensor arrays.

The teaching effectiveness was evaluated using four different methods, including student assessment, lab assistant assessment, instructor self-evaluation and the review of technical results. These individual assessments were more meaningful when they were combined, producing more comprehensive results.

Student assessments traditionally dominated as a major assessment method as it is a result of an interaction between the instructor and the student who was affected directly by the teaching method. In this particular assessment, as there was no exam taken by the student, the assessment was performed more by student observation in different events. The student was asked to answer a few standard questions with a scale of 1-7 rating. Table 2 shows the major questions asked in the student evaluation form. The evaluation results were processed and revealed a 86% success in teaching from student's standpoint.

Table 2: Major questions in student evaluation form

Question	Rating (1-7)
How would you rate the difficulty of this course?	
Does the professor appear well prepared for this course?	
How well does the professor communicate with student?	
How well does the professor motivate student to do the best work?	
How knowledgeable does the professor appear about the subject?	
What is the professor's attitude toward the subject matter of the course?	
Is the professor willing to use a variety of activities to promote student learning?	
What was the professor's attitude toward the student?	
How available is the professor for help outside of class?	
How reasonable/fair are the professor's grading criteria?	
To what extent are the professor's presentations/instructions generally thought provoking?	
Was the feedback from the professor provided in a timely manner?	
How would you rate the overall teaching effectiveness of the professor?	

Table 3: Major questions in lab assistant evaluation form

Question	Rating (1-7)
How knowledgeable does the professor appear about the subject?	
Was the course objectives clear?	
Were the course activities organized?	
Were the course documentation/instructions in an appropriate level and easy to understand?	
Does the professor appear well prepared for this course?	
Does the professor have enthusiasm, energy, and confidence about the course?	
Is the professor willing to use a variety of activities to promote student learning?	
Does the professor make precise explanation and clear discussion with student?	
Was the attitude of professor toward students appropriate?	
Was the professor aware of student needs?	
Was the professor able to answer the student questions?	
Does the professor interact enough with student?	
Did the professor use visual aids (eg. projector, board, etc.) to demonstrate the work to student?	
Was the feedback from the professor provided in a timely manner?	
Is the professor willing to use a variety of activities to promote student learning?	

As the second method of the assessment, the lab assistant also evaluated the teaching effectiveness. This method of assessment is considered as a peer review. The objective of the evaluation was to help the instructor on formative decisions. The assessment results complement items such as course content and objectives that the student would not be able to assess. It provides the most valid results after student evaluation. The lab assistant was asked to answer few questions with a scale of 1-7 rating as presented in Table 3. The results were processed with 93% success in teaching from lab assistant's perspectives.

As the third evaluation method, the instructor performed a self-assessment used in evaluating teaching effectiveness. This type of assessment might not be an accurate evaluation, however it would help the instructor identify the areas that may need some adjustment in the teaching method). The instructor particularly revisited the lecture slides, lab instructions, project instructions, and safety manual and tests. Although most of the documentation were correct, there were a few areas that required a fine tune. Therefore, the instructor concluded the results of the self-assessment as a high success rate. Several people have already performed this type of assessment and reported that it was an inaccurate method of assessment for teaching effectiveness. They mentioned that the assessment is more formative helping the instructor for possible corrections rather than a summative method. Although the instructor's self-assessment was not that accurate, we found that it could augment the student and lab assistant assessments.

The fourth method of assessment performed by all three parties was based on the technical results of the microfabrication. A comprehensive discussion of the results is covered in the next subsection. In general, it is believed that this method of the assessment provides the most accurate feedback on the teaching effectiveness as the results reveal how well the student was able to use these skills to make a flawless device. The process of learning microfabrication techniques requires a long program including several hands-on courses. As discussed earlier in the design section, the instructor initially created tasks for four different design configurations, from least likely to most likely to succeed. The technical results showed that configurations 3.1 and 4.1 were satisfactorily fabricated. As a result, the microfabrication skills were successfully developed in the student within the course.

In summary, technical evaluation may provide the most accurate assessment on teaching evaluation. Although the self-evaluation may not be a reliable method of assessment alone, the lab assistant evaluation that can be considered as a peer evaluation along with the student evaluation may augment the other methods of evaluations. It is believed that these four methods together countered the possible tendency of each individual method and provided a full picture of teaching effectiveness. Overall, it was found that the teaching method proposed in this paper was successful. The promising results of this teaching methodology lead the instructor to plan similar classes next year.

Technical Results

The fabricated silicon dies were assessed using an optical profilometer and microscope. Figure 6 shows the optical images of the wet etched cavities on the silicon wafer. Further assessment using the optical microscope revealed flawless cavities in all four configurations. Figure 7 depicts the piezoresistors formed by boron doping of the silicon wafer in the furnace. Optical evaluations showed that all piezoresistors turned out to be fine although their dimensions were slightly off most probably because of the overdevelopment of the photoresist due to the small dimensions of the piezoresistors.

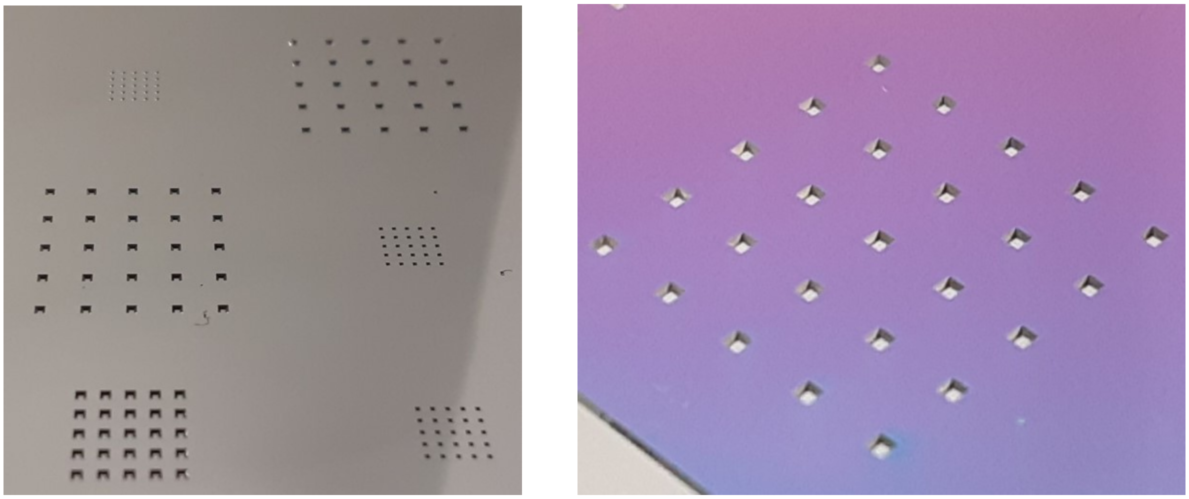


Figure 6: Optical images of wet etched cavities on the silicon wafer.

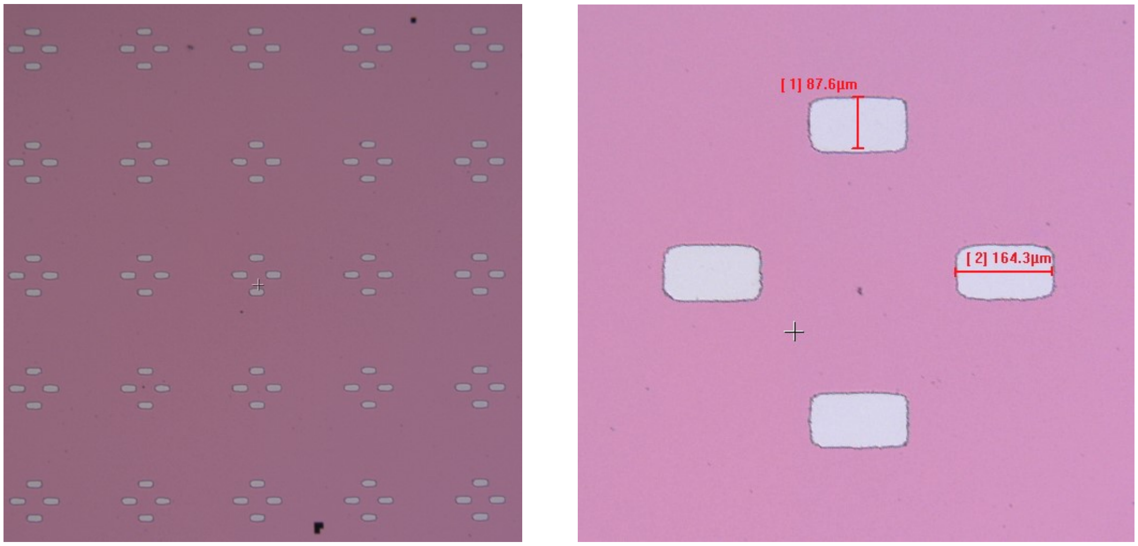


Figure 7: Piezoresistors formed by boron doping of the silicon wafer in the furnace.

Figures 8 shows optical images of aluminum conductors taken from different locations of the sensor array. Forming flawless aluminum conductors was the most challenging portion of the fabrication as the gaps between the conductors were so small due to the high density of the lines connecting to the pads in the surrounding of the arrays as shown in Figure 9. While all other configurations turned out to be acceptable after the inspection, configurations 1.1 and 2.1 did not have enough spacing between their features and failed to fully develop during the MEMS fabrication process. Figure 8(a) shows the final aluminum traces for a Wheatstone bridge formed on the wafer for a sample sensor array for configuration 3.1. Profilometer readings indicated that the aluminum layer was approximately 2 µm thick. The development of the traces varied depending on their direction, though they were all given the same 50 µm spacing from each other. If the conductors were aligned to the horizontal orientation, the lines were distinct and electrically insulated from each other, but if the conductors were aligned to the vertical orientation, the lines merged together and created short circuits. These issues found to be related to the mask laser plotter as the plotter created horizontal and vertical lines with a radically different resolution.

Figure 8(b) displays a sample sensor array for configuration 4.1. This configuration remained short circuit free although the traces did exhibit the same difference in spacing as configuration 3.1, but to a lesser degree. The configuration 4.1 showed the integrity of the traces in the vertical orientation, which got rather close to touching each other but not yet. This behavior is consistent across all the sensor arrays with the configuration 4.1, thus indicating its potential for being used in the fully operational pressure sensor array design.

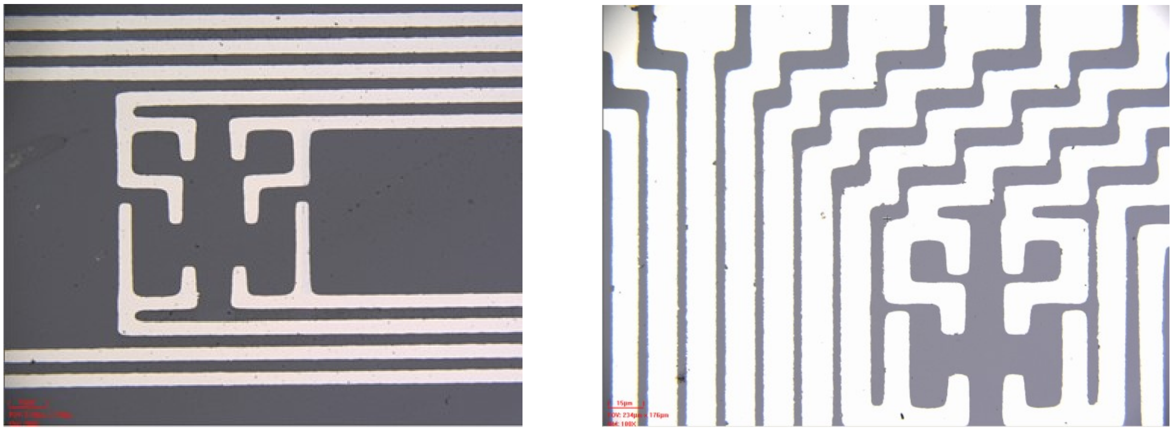
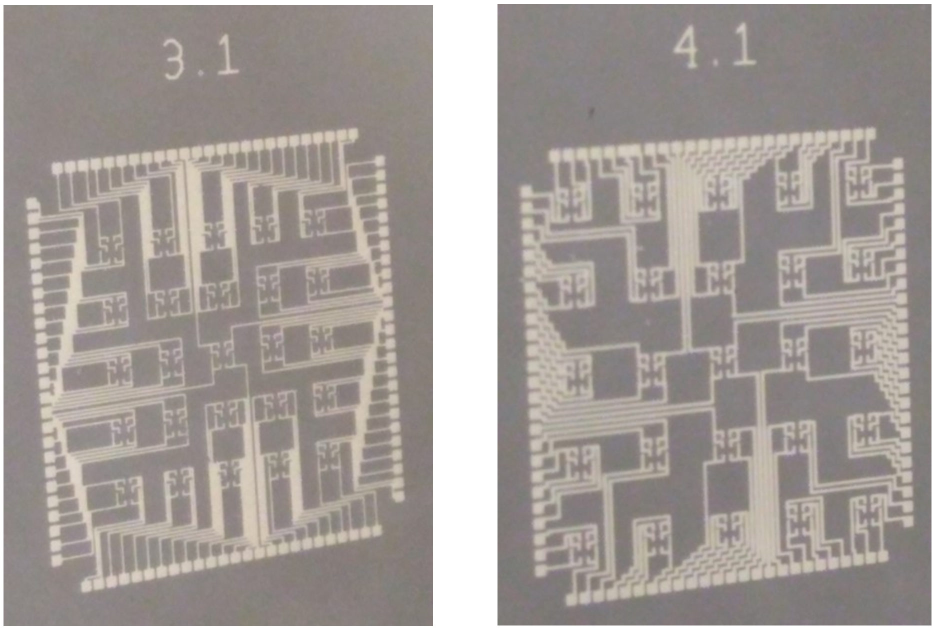

(a) (b)

Figure 8: Optical microscopic images of aluminum conductors on silicon die for configurations 3.1 (a) and 4.1 (b).



(a) (b)

Figure 9: Fabricated pressure sensor array for configurations 3.1 (a) and 4.1 (b).

Figure 9 shows the final arrays for configurations 3.1 and 4.1. The microscopic images indicate that configuration 4.1 yielded the highest success rate at passing the device integrity tests, although configuration 3.1 would be almost as successful if slightly more spacing was given between the traces. Both device configurations will be examined in more detail and developed in future projects for bringing the pressure sensor array into a functioning reality.

Conclusions

This paper explored an undergraduate mechanical engineering student’s venture into designing and fabricating a MEMS pressure sensor array for potential application on a microfluidic lab on chip solution. The project was initiated by the instructor to get the student up to speed as fast as possible, ready for the next project assignment. The idea behind this project was to help the student learn essential microfabrication processes required for fabricating a MEMS device rather than developing a functional product. The student was assisted by the instructor with finding a novel idea for the device, discussing the details of the design, providing the detail of microfabrication process flow, etc. The fabrication training was based on an apprentice style arrangement where the student received exemplary behavior and advice from an experienced lab assistant in fabricating other devices that featured the same fabrication techniques, equipment, and materials to process. He then used these new skills to construct the actual MEMS device. Once the prototype sensor arrays were fabricated, they were examined for manufacturable reliability as a future testbed for furthering research into MEMS pressure sensor arrays. It was found that the student was able to complete the basic learning processes within an academic semester. The teaching effectiveness was evaluated using four different resources, including student assessment, lab assistant assessment considered as a peer review, instructor self-evaluation and the review of technical results. Combination of the individual assessments created more comprehensive results. It was concluded that the teaching method proposed in this paper was successful. Observations regarding the learning experience and skill development in the undergraduate student from the instructor’s and lab assistant’s perspectives were provided. In addition, comments regarding the student's motivation, confidence, risks, failures, frustrations, achievements, and reflections were presented from the student’s perspectives.

References

[1] Nisar A, Afzulpurkar N, Mahaisavariya B, Tuantranont A. MEMS-based micropumps in drug delivery and biomedical applications. Sensors and Actuators B: Chemical. 2008 Mar 28;130(2):917-42.

[2] Tang WC, Lee AP. Defense applications of MEMS. Mrs Bulletin. 2001 Apr;26(4):318-9.

[3] Osiander R, Darrin MA, Champion JL. MEMS and microstructures in aerospace applications. CRC press; 2018 Oct 3.

[4] Marek J. MEMS for automotive and consumer electronics. In2010 IEEE International Solid-State Circuits Conference-(ISSCC) 2010 Feb 7 (pp. 9-17). IEEE.

[5] Wong JE, Lang JH, Schmidt MA. An electrostatically-actuated MEMS switch for power applications. InProceedings IEEE Thirteenth Annual International Conference on Micro

Electro Mechanical Systems (Cat. No. 00CH36308) 2000 Jan 23 (pp. 633-638). IEEE.

[6] Ko CT, Chen KN. Wafer-level bonding/stacking technology for 3D integration. Microelectronics reliability. 2010 Apr 1;50(4):481-8.

[7] Linder C, Paratte L, Grétillat MA, Jaecklin VP, De Rooij NF. Surface micromachining. Journal of Micromechanics and Microengineering. 1992 Sep;2(3):122.

[8] Kovacs GT, Maluf NI, Petersen KE. Bulk micromachining of silicon. Proceedings of the IEEE. 1998 Aug;86(8):1536-51.

[9] Grayson AC, Shawgo RS, Johnson AM, Flynn NT, Li Y, Cima MJ, Langer R. A BioMEMS review: MEMS technology for physiologically integrated devices. Proceedings of the IEEE. 2004 Nov 8;92(1):6-21.

[10] Bassous E, Taub HH, Kuhn L. Ink jet printing nozzle arrays etched in silicon. Applied Physics Letters. 1977 Jul 15;31(2):135-7. University/Government/Indusry Microelectronics Symposium, Boise, 2003.

[11] Verpoorte E, De Rooij NF. Microfluidics meets MEMS. Proceedings of the IEEE. 2003 Jun 25;91(6):930-53.

[12] Huang C, Tsou C. The implementation of a thermal bubble actuated microfluidic chip with microvalve, micropump and micromixer. Sensors and Actuators A: Physical. 2014 Apr 1;210:147-56.

[13] Nguyen NT, Huang X, Chuan TK. MEMS-micropumps: a review. J. Fluids Eng.. 2002 Jun 1;124(2):384-92.

[14] Sanjay ST, Zhou W, Dou M, Tavakoli H, Ma L, Xu F, Li X. Recent advances of controlled drug delivery using microfluidic platforms. Advanced drug delivery reviews. 2018 Mar 15;128:3-28.

[15] Pol R, Céspedes F, Gabriel D, Baeza M. Microfluidic lab-on-a-chip platforms for environmental monitoring. TrAC Trends in Analytical Chemistry. 2017 Oct 1;95:62-8.

[16] Kjeang E, Djilali N, Sinton D. Microfluidic fuel cells: A review. Journal of Power Sources. 2009 Jan 15;186(2):353-69.

[17] Ashraf MW, Tayyaba S, Afzulpurkar N. Micro electromechanical systems (MEMS) based microfluidic devices for biomedical applications. International journal of molecular sciences. 2011 Jun;12(6):3648-704.

[18] Grafton MM, Maleki T, Zordan MD, Reece LM, Byrnes R, Jones A, Todd P, Leary JF. Microfluidic MEMS hand-held flow cytometer. InMicrofluidics, BioMEMS, and Medical Microsystems IX 2011 Feb 14 (Vol. 7929, p. 79290C). International Society for Optics and Photonics.

[19] Pal P, Sato K. Fabrication methods based on wet etching process for the realization of silicon MEMS structures with new shapes. Microsystem technologies. 2010 Jul 1;16(7):1165-74.

[20] Pal P, Sato K, Gosalvez MA, Shikida M. An improved anisotropic wet etching process for the fabrication of silicon MEMS structures using a single etching mask. In2008 IEEE 21st International Conference on Micro Electro Mechanical Systems 2008 Jan 13 (pp. 327-330). IEEE.

[21] Yoon YK, Park JH, Allen MG. Multidirectional UV lithography for complex 3-D MEMS structures. Journal of microelectromechanical systems. 2006 Oct 30;15(5):1121-30.

[22] Kottapalli AG, Asadnia M, Miao JM, Tan CW, Barbastathis G, Triantafyllou M. Polymer MEMS pressure sensor arrays for fish-like underwater sensing applications. Micro & Nano Letters. 2012 Dec 1;7(12):1189-92.

[23] Dusek J, Kottapalli AG, Woo ME, Asadnia M, Miao J, Lang JH, Triantafyllou MS. Development and testing of bio-inspired microelectromechanical pressure sensor arrays for increased situational awareness for marine vehicles. Smart Materials and Structures. 2012 Dec 6;22(1):014002.

[24] Takao H, Sawada K, Ishida M. Monolithic silicon smart tactile image sensor with integrated strain sensor array on pneumatically swollen single-diaphragm structure. IEEE Transactions on Electron Devices. 2006 Apr 24;53(5):1250-9.

[25] Frechette L, Modi V, Miller F, Farmer KR. Hands-on MEMS. InProceedings of the 15th Biennial University/Government/Industry Microelectronics Symposium (Cat. No. 03CH37488) 2003 Jul 2 (pp. 157-160). IEEE.

[26] Lee SJ, Gleixner S, Hsu TR, Parent DW. A development framework for hands-on laboratory modules in Microelectromechanical systems (MEMS). InProceedings of the ASEE Annual Meeting 2006.

[27] Adams T. An Undergraduate MEMS Course for Everyone. age. 2004;9:1.

[28] Berk RA. Survey of 12 strategies to measure teaching effectiveness. International journal of teaching and learning in higher education. 2005;17(1):48-62.

[29] American Educational Research Association, American Psychological Association, National Council on Measurement in Education, Joint Committee on Standards for Educational, Psychological Testing (US). Standards for educational and psychological testing. Amer Educational Research Assn; 1999.

[30] Chen Y, Hoshower LB. Student evaluation of teaching effectiveness: An assessment of student perception and motivation. Assessment & evaluation in higher education. 2003 Jan 1;28(1):71-88.

[31] Arreola RA. Developing a comprehensive faculty evaluation system. Magna Publications; 2004.

[32] Centra JA. Reflective Faculty Evaluation: Enhancing Teaching and Determining Faculty Effectiveness. The Jossey-Bass Higher and Adult Education Series. Jossey-Bass Inc., 350 Sansome St., San Francisco, CA 94104; 1993.

[33] Miller JE, Seldin P. Changing practices in faculty evaluation. Academe. 2014 May 1;100(3):35-8.

[34] Coughlin T, Rashidi R. A powerless iron oxide based magnetometer. Microsystem Technologies. 2020 Feb 22:1-2.

[35] DeGraff A, Rashidi R. Ferrofluid transformer-based tilt sensor. Microsystem Technologies. 2020 Feb 21:1-8.

[36] Bianconi J, Hallett J, Pealo J, Rashidi R. A hybrid piezoelectric and inductive rotational energy harvester. InIOP Conference Series: Materials Science and Engineering 2019 Sep (Vol. 626, No. 1, p. 012004). IOP Publishing.

[37] Mbaye A, Kreamer C, Zink L, Fredenburg M, Rashidi R. 3D printed micro check valve for biomedical applications. InIOP Conference Series: Materials Science and Engineering 2018 Sep (Vol. 417, No. 1, p. 012041). IOP Publishing.