

MEMSlab: A Practical MEMS Course for the Fabrication, Packaging, and Testing of a Single-Axis Accelerometer

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Abstract—A microelectro-mechanical systems (MEMS) laboratory course (MEMSlab) in the Mechanical and Process Engineering Department at the Swiss Federal Institute of Technology (ETH Zurich), is presented. The course has been taught for four years and has been attended primarily by Master's students from mechanical and electrical engineering; since fall 2006, the course has been required within the Master of Micro and Nanosystems curriculum. Students participating in the MEMSlab course learn the operational principles of comb-structure accelerometers, as well as how to fabricate, package, and test single-axis accelerometers, thereby being exposed to the multiple disciplines and practical topics that are involved in the production of MEMS and microelectronics. Based upon the course assessments, which are summarized and discussed, one of the benefits of MEMSlab is the course format. This format, which includes a dedicated course text, referred to as the “script,” and two introductory lecture sessions, has allowed students without prior semiconductor physics or process experience to participate fully in the course and to learn the major elements of MEMS fabrication. The MEMSlab course provides students at the ETH Zurich with their sole opportunity to experience clean room microfabrication through a structured course setting, since there are no other solid-state device fabrication laboratory courses offered at the ETH Zurich.

Index Terms—Electrical engineering education, fabrication, laboratory course, mechanical engineering education, microelectro-mechanical systems (MEMS), semiconductor.

I. INTRODUCTION

THE microelectro mechanical systems laboratory (MEMSlab) course provides students with the opportunity to gain practical experience in the processes used in microsystems (MEMS) technologies, to learn the theory behind engineering a microsystem, and to apply this theory in practical work, thereby developing an understanding of the capabilities and limits of the technology. The microsystem which is fabricated and tested is a one-axis accelerometer with comb structure as shown in Fig. 1. The course provides a vital hands-on laboratory experience [1] which is not otherwise available through lecture courses in the curriculum of students

Manuscript received October 5, 2007; revised December 19, 2007. Current version published February 4, 2009. This work was supported in part by the Fund for Innovative Educational Programs (FILEP) and ETH Zurich.

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Digital Object Identifier 10.1109/TE.2008.919807

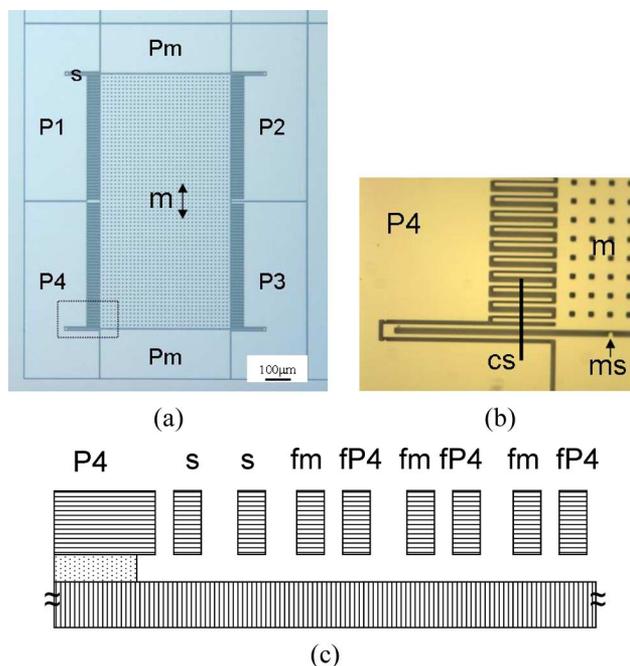


Fig. 1. (a) Photograph of a single-axis accelerometer fabricated in the MEMSlab where P1, P2, P3, and P4 are bonding pads for the 4 quadrants of fixed-position comb fingers, and Pm are bonding pads for the movable seismic mass, m , to which the (movable) comb fingers are attached. The acceleration axis is shown by the arrow. The mass, m , is suspended by four springs, s , consisting of two cantilever beams each. The dimension of the mass is $500\ \mu\text{m} \times 1000\ \mu\text{m}$. (b) Higher magnification photograph of the area contained within the dotted-line box shown in the lower left portion of Fig. 1(a). The spring which is connected to Pm and the seismic mass, the fixed-position comb fingers which are attached to P4, and the movable seismic mass with attached comb fingers are clearly visible. (c) Cross-sectional schematic taken along the line labeled “cs” in Fig. 1(b). The $5\text{-}\mu\text{m}$ -thick silicon device layer is shown with horizontal line pattern, the $2\text{-}\mu\text{m}$ -thick silicon dioxide sacrificial layer is shown with dotted pattern, and the $400\text{-}\mu\text{m}$ -thick bulk silicon substrate is shown with vertical line pattern (not to scale). The bond pad P4 is anchored to the silicon substrate by the silicon dioxide. The 2-cantilever-beam spring is schematically represented by “s.” The comb fingers which are connected to the movable seismic mass are labeled “fm,” and the fixed-position comb fingers which are connected to the anchored bond pad P4 are labeled “fP4.”

of electrical engineering (EE), mechanical engineering, MEMS and microelectronics.

This course has multiple goals and benefits. Students learn what a clean room is and why it is required (humidity, temperature, and particle control) when fabricating MEMS or microelectronics. Students have the opportunity to experience practical clean room fabrication, handling wafers and equipment, and developing proper documentation. A further aspect which is also of tremendous importance is safety; students are introduced

to material safety data sheets (MSDS) for chemical safety, and potential hazards are identified including high voltages, high temperatures (hotplates), ultraviolet (UV) radiation, gasses, fire, and explosive materials. The influence of the individual process steps and the overall process on the design and performance of the MEMS is made clear. The limits, capabilities, interaction, and benefits of various process technologies are discussed. This discussion is reinforced by comparing the measured values with theoretical or expected values and performing error analysis. Furthermore, the importance of testing and evaluation is learned, and put into practice, during and after the completion of individual process steps and at the completion of the MEMS packaging. In the following sections, the course structure is presented, the individual course modules and associated teaching goals are discussed, and student and tutor comments about the course, along with the subsequent changes and improvements to the course, are summarized.

II. COURSE STRUCTURE

The course was developed and taught between 2003 and 2007 and is organized such that students are exposed to as many aspects as possible related to MEMS, while keeping the modules sufficiently simple to allow the fabrication and testing to take place within seven half-day laboratory sessions. Although some students are familiar with basic fabrication technology from an introductory solid state device engineering lecture course, the first two half-day meetings of the MEMSlab course are lectures during which the accelerometer design, the basic process technologies, and the specific process steps and equipment are presented. A script was prepared for the course and is distributed to students (and is available online to enrolled students). The script and lectures serve to allow students with no prior studies in MEMS or fabrication to participate in the course and provides all students with all the information they need for the course. Table I gives an overview of the script content, and this content is presented in lectures that are held during the first two meetings of the course. Chapters 3–9 cover the practical course modules. Each chapter contains an introduction to the module with module goals, safety instructions, a list of references, and preparation guidelines that describe the preparation to be done by the students prior to coming to the course meeting, for each of these practical modules. The preparation guidelines include control questions and suggestions for items to be included in the student presentation (described later) and reports. Additional information on the individual modules is given in Section III, Course Modules.

After the first two lectures, the students are divided into groups of three for the practical laboratory portion of the course, which consists of seven half-day sessions (chapters 3–9 of Table I). Each module is tutored by a Ph.D. student from the Micro and Nanosystems Group. Students are placed in groups for several reasons: to encourage efficient laboratory work, to compensate for and benefit from the varying backgrounds of the students, to develop communication, cooperation, and organization skills, and to allow students to experience the sort of group dynamics that replicate an industrial fabrication setting where many disciplines and individuals are working

together towards an end goal. Groups typically consist of at least one EE Master's student, and one mechanical engineering (ME) Master's student; the third group member may be a Master's student in EE, ME, physics, materials, chemistry, biology, or Micro and Nanosystems (Micro and Nanosystems Master's students typically have an EE or ME undergraduate background). The backgrounds of the 80 students who took the course (2004–2007) were 53.75% ME, 38.75% EE, 2.5% chemistry, 2.5% physics, 1.25% materials, and 1.25% biology. By mixing the students of different disciplines in the groups, they can learn from each other and benefit from their different backgrounds, since topics from both EE and ME, and from basic science disciplines, are relevant to the MEMSlab course and to microsystems generally [1]. Efficiency is achieved when working in groups because this prevents students in the laboratory from waiting to use equipment, and helps to ensure that safety is maintained. Furthermore, the groups are stagger-started in the laboratory. The first group starts processing during the third week of the semester, the second group starts a week later, the third group starts a week later, etc. With this scheme, a maximum of five groups (15 students) can participate during the 13-week semester. For example, the fifth group spends the first two weeks in lectures (along with the other enrolled students), then this group waits four weeks, and starts the laboratory during the seventh week of the semester and finishes during the thirteenth week of the semester (having had seven laboratory sessions). With the group system and staggered start, the course can be staffed with seven tutors, and run efficiently without overloading the clean room facility (which is not a dedicated clean room for this course, but rather is a general-use research clean room at the ETH Zurich). No effect upon student performance, based upon grades received, has been seen between the students in the stagger-started groups.

The MEMSlab has also been conducted in a short-course format that was taught during the semester break in the summer months. In that case, groups were able to complete the laboratory portion of the course during five full days, and the groups started their practical work staggered by two days, in order for five groups to complete the course within thirteen days (2.5 weeks). Feedback was mixed, but generally students liked the intense, focused laboratory work. However, this format was a strain on the clean room, which had to be primarily used only for the course participants, while other Ph.D. student research was delayed. In the normal semester format, the course is less disruptive for the other clean room users, since the clean room is only occupied by the MEMSlab course participants during one afternoon per week. Furthermore, in the short-course format, a maximum of 15 students per year can participate, while 30 students per year can participate (15 per semester) with the course offered during the semesters.

The structure of having different Ph.D. student tutors teaching each module also emulates an industrial setting in which an engineer or small group of engineers is responsible for each process and test module, and gives students the opportunity to learn from several tutors using different techniques. This approach is beneficial to tutors and students alike, as they have the opportunity to meet each other and discuss potential semester

TABLE I
TOPICS IN THE MEMSLAB SCRIPT. THESE TOPICS ARE ALSO PRESENTED DURING THE TWO INTRODUCTORY LECTURES

| Script chapter | Topics |
|--|--|
| 1. General introduction | Laboratory rules, safety, cleanliness, hazards, and emergency procedures. Cleanroom work procedures: equipment and wet benches, cleanroom clothing. Course organization and assessments: presentations, tests, report. Accelerometer overview: design considerations, SOI wafer specifications, device and mask layout, process flow and run sheet. |
| 2. Design of a micro accelerometer | Modeling of accelerometers (general): equation of motion, static and harmonic response, eigenfrequencies, damping, spring stiffness, capacitive readout. Trade-off between pull-in voltage and sensitivity. Sensor design/layout (specific): proof mass, spring stiffness, eigenfrequencies, damping (Couette-flow, Stokes-flow, Hagen-Poiseuille flow, overall), relative change in capacitance at operation, sensor characterization guideline. |
| 3. Photolithography | Description of photolithography processes: optical (contact, proximity, and projection), positive and negative processes, photolithography wavelengths. Photolithography masks. Development: over and underdevelopment. Processes for the course: process steps, process development, safety. Appendices: Mask aligner, wet bench, and photoresist description. |
| 4. Dry etching | Etching techniques: wet and dry etching, isotropic and anisotropic profiles. Plasma dry etching: plasmas and discharges, physics of plasmas, RF plasmas. Possible defects and causes: pattern transfer, sidewall slope, etch depth, surface roughness, photoresist, notching. Setup, handling and theory: RIE, ICP, equipment description and control software. WLI (white light interferometry) profiling. Measurement principles & theory. |
| 5. Back-end process I: dicing | Dicing: dicing of suspended structures, debris from sawing process, protection of MEMS structures with photoresist. MEMS packaging by wafer bonding. Differences between IC and MEMS packaging. Overview of the dicing process: dicing tape, sawing, saw parameters. Appendix: wafer saw media, saw description, control and procedure. |
| 6. Sacrificial layer etching and critical point drying | Overview of possible sacrificial layers and release techniques, pros and cons. Etch selectivity and factors that affect the selectivity and etch rate. Sacrificial layer etching: HF etch of silicon dioxide, stiction and surface tension. Safety: working with HF, HF emergency kit. Supercritical point drying using carbon dioxide, CO ₂ phase diagram. Process and equipment description: HF etch, supercritical point dryer. |
| 7. Back-end process II: packaging | Mounting of silicon die in packages: general and specific theories and processes. Wire bonding: physics, bonding techniques (ball, wedge) and variables. Process description, pin assignment, bonder settings, evaluation of the process. |
| 8. Electrical readout | Capacitor fundamentals. Differential capacitive sensing: linearization of signal. Electrostatic force, torque, pull-in voltage. Electrical model of the accelerometer including parasitics. Readout circuit: AC modulation, amplitude modulation, charge integrator, differential to single-ended instrumentation amplifier, demodulator (multiplier & low pass filter), noise sources. Transfer characteristic and capacitance resolution. Chosen components (ICs and discrete components) for readout circuit PCB. Probe station test setup and tests, LCR meter test setup and tests. |
| 9. Sensor characterization | Terms & definitions used for sensor description, characterization, & specification. Random and systematic errors, error sources, propagation and analysis. Experimental setup, reference sensor, equipment. Procedure for sensor characterization. Appendix: data sheets of reference sensor, oscilloscope, function generator, and DC voltage supplies. |
| 10. MSDS | Material safety data sheets (MSDS) of solvents, photoresists, developers, acids, and gasses used in the processing. |

projects or Master's thesis projects offered within the Micro and Nanosystems Group and other research groups.

Students are evaluated during the course by means of daily tests and student presentations, as well as a final report. The tests, presentations, and reports are in English. The written daily tests are conducted at the beginning of each practical laboratory session and questions are related to the work that will be done during the laboratory session and the associated safety aspects. The daily tests are meant to motivate each of the students to prepare for the laboratory session and are based upon the material provided in the script. Following the daily test, one student gives a 15-minute oral presentation, similar to the length of a conference presentation, on the topic of the day's laboratory session.

The purpose of the presentation is to ensure that at least one student within the group will thoroughly prepare and understand the subject-matter and procedure of the module. Also, students are given an opportunity to learn how to structure and make presentations, as well as to learn from their colleagues within the group. After the presentation, the tutor reinforces the important topics and the group discusses any remaining issues before entering the laboratory.

A final report is required, which provides students with the opportunity to document and present the theory and results of the coursework, and to gain experience in technical writing. The suggested format of the report and individual chapters is provided in the MEMSLab script. A laboratory module is de-

TABLE II
PHOTOLITHOGRAPHY STEPS AND ASSOCIATED EDUCATIONAL TOPICS

| Steps | Educational topics |
|------------------------|---|
| 1. Wafer cleaning | Wetbench, ultrasonic bath, and barrel etcher operation. Working with solvents safely, disposal. Reading and understanding MSDS. |
| 2. Photoresist coating | HMDS vapor priming system, photoresist spinner, and hotplate operation. Photoresist sensitivity to humidity. |
| 3. Exposure | Contact aligner operation, including measurement of exposure intensity and calculation of exposure time to achieve desired dose. Contact alignment: soft, hard, or vacuum contact and the impact on resolution. Underexposure and overexposure. |
| 4. Development | Underdevelopment & overdevelopment (related to under/over exposure). |
| 5. Inspection | Optical microscope operation. Defect identification. Underdeveloped (underexposed) structures may be reworked possibly with additional development. Entire process sequence can be reworked if overdeveloped (overexposed). Process (photolithography) variations and their effects. Resolution. Dimensional sizes on mask versus on the wafer. |

scribed in each chapter of the report, and the chapter content is structured similarly to that of technical papers with introduction, theory, experimental, results, and conclusions sections. Grades are based upon both the individual and group effort. The students are graded individually on their daily test and presentation performance, while all three students in the group receive the same grade on the final report. Thus, emphasis is placed on both individual and group performance.

The MEMSlab course has been, since fall 2006, one of five required courses within the Master of Micro and Nanosystems curriculum. The Master of Micro and Nanosystems curriculum is a joint program offered through the EE and ME departments and has been developed with the aim of providing an interdisciplinary education for engineers. An interdisciplinary education is recognized as valuable for engineers in disciplines such as MEMS [1], [2]. The five required courses within the masters program focus on material and surface properties, quantum mechanics, physical modeling and simulation, microscale and nanoscale devices and systems, and the MEMSlab. The benefits of practical experience offered through the MEMSlab course being highly valued by both industry [2] and academia, underlay the decision to make this a required course of the Master of Micro and Nanosystems curriculum. The professors who are involved with the program and serve as advisors for Master's theses are in the departments of EE, ME, physics, and physical chemistry.

III. COURSE MODULES

The seven course modules which are carried out in the laboratories, in chronological order, are photolithography, dry etching, dicing, release (sacrificial layer etching and supercritical point drying), packaging, electrical readout, and sensor characterization. While in the laboratory, the processing is documented on run sheets that are accessible online. Additional electronic data (such as digital photos taken in the laboratory) are also saved online.

The course format was developed to give students an opportunity to participate in as many as possible of the fabrication, packaging, and evaluation steps in the production of MEMS, while keeping the modules sufficiently simple to allow their completion within seven half-day laboratory sessions. The students do not participate in the design or layout of the accelerometers due to schedule constraints. Emphasis is placed on fabrication and

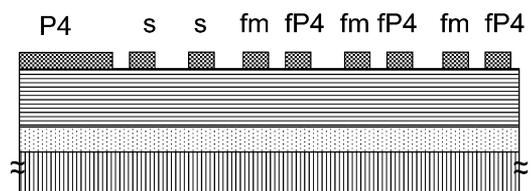


Fig. 2. Cross-sectional schematic after the photolithography process. Cross-section is made along the “cs” line shown in Fig. 1(b). Photoresist is represented by the checkerboard patterned areas, the 5- μm -thick silicon device layer is shown with horizontal line pattern, the 2- μm -thick silicon dioxide sacrificial layer is shown with dotted pattern, and the 400- μm -thick bulk silicon substrate is shown with vertical line pattern (not to scale). The 2-cantilever-beam spring is schematically represented by “s.” The comb fingers which are connected to the movable seismic mass are labeled “fm,” and the fixed-position comb fingers which are connected to the anchored bond pad P4 are labeled “fP4.”

packaging methods and techniques, and also on measurement and evaluation of results at every step. Measurements and evaluation are done frequently, to convey the message that because fabrication, packaging, and testing are costly, is necessary to evaluate progress and functionality continually. In production environments, nonfunctional wafers are halted, and nonfunctional components may not be packaged. Furthermore, recurrent evaluation and testing provide the means to gain a better understanding of the influence of processes and packaging on the design and performance of the accelerometer specifically, and MEMS in general. An overview of the process and of each of the modules, including teaching and technical goals, is described later. Furthermore, prior to and after completion of the clean room laboratory modules, students and tutors check and turn on and off the various required media such as pumps, gasses, water, etc., that are required to work in the clean room. This responsibility provides a glimpse of the infrastructure necessary to operate the clean room.

The first module is *photolithography*. During the module, one 4-inch silicon on insulator (SOI) wafer and three silicon wafers are processed. The SOI wafer has a 400- μm -thick bulk layer, a 2- μm -thick oxide layer, and a 5- μm -thick device layer with boron doping (resistivity of $\sim 0.01 \Omega\text{mm}$). The silicon wafers are included as process monitor wafers for the photolithography, dry etching, and dicing processes, as well as to allow each of the three group members to perform all of the steps. The photolithography steps and several of the related educational topics are summarized in Table II. A schematic

TABLE III
DRY ETCHING STEPS AND ASSOCIATED EDUCATIONAL TOPICS

| Steps | Educational topics |
|--------------------|--|
| 1. Dry etching | RIE and ICP principles, system operation and configurations (diode or triode). Bosch process: alternating plasma chemistry for etch and passivation. Plasma heating, hardening and etching of photoresist mask. Etch selectivity and uniformity. |
| 2. Etch evaluation | White light interferometer system principles, configuration, and operation. Limits: aspect ratio, spot size, interference; comparison to alternate methods. Data evaluation, size dependent etch rate, uniformity. |

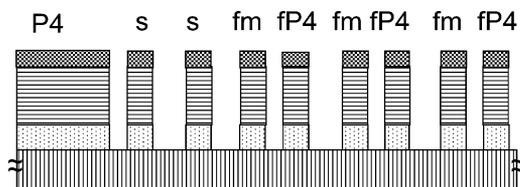


Fig. 3. Cross-sectional schematic after the dry etch process. Cross-section is made along the “cs” line shown in Fig. 1(b). Photoresist is represented by the checkerboard patterned areas, the $5\text{-}\mu\text{m}$ -thick silicon device layer is shown with horizontal line pattern, the $2\text{-}\mu\text{m}$ -thick silicon dioxide sacrificial layer is shown with dotted pattern, and the $400\text{-}\mu\text{m}$ -thick bulk silicon substrate is shown with vertical line pattern (not to scale). The 2-cantilever-beam spring is schematically represented by “s.” The comb fingers which are connected to the movable seismic mass are labeled “fm,” and the fixed-position comb fingers which are connected to the anchored bond pad P4 are labeled “fP4.”

cross-section of a portion of the device after the completion of the photolithography process is shown in Fig. 2. The mask that is used is populated with two accelerometer designs (one called robust, and one called sensitive). The robust design (Fig. 1) has a smaller footprint (seismic mass x-y dimension $0.5 \times 1\text{ mm}$, compared to $1 \times 2\text{ mm}$ for the sensitive design), fewer and shorter comb fingers (124 fingers of $50\text{ }\mu\text{m}$ length compared to 360 fingers of $70\text{ }\mu\text{m}$ length for the sensitive design), and a larger minimum gap distance between comb fingers ($1.5\text{ }\mu\text{m}$ compared to $1.25\text{ }\mu\text{m}$ for the sensitive design). Therefore, the robust design is less sensitive and has a higher pull-in voltage compared to the sensitive design [3].

The second module is *dry etching*. The patterned photoresist (from the previous step) provides the mask for the dry etching sequence which consists of three steps. First, reactive ion etching (RIE) is performed for one minute to etch any native silicon dioxide which may be present after the wafers have been waiting for a week since the previous process step. Then, an inductively coupled plasma (ICP) is used to etch the $5\text{-}\mu\text{m}$ -thick silicon device layer using the “Bosch process” [4]. The final etch step is again performed in the RIE to etch the $2\text{ }\mu\text{m}$ silicon dioxide layer. It was found that by using RIE to etch the silicon dioxide anisotropically, the subsequent release step in liquid hydrofluoric acid (HF) was more uniform and controlled. The dry etch process is evaluated using nondestructive and destructive methods. White light interferometry (*NewView 5000* from ZYGO) [5] is used to measure the etch depth on the SOI wafer, while one of the silicon wafers is cross-sectioned (a destructive process) and the etch depth is measured using optical microscopy. The dry etching module and several educational topics are summarized in Table III. A schematic cross-section of a portion of the device after the completion of the dry etching process is shown in Fig. 3.



Fig. 4. Photograph of the chip holder which can be used for wet processing of twenty-four $3\text{ mm} \times 3\text{ mm}$ die. The handle is removable so that the base with the chips can be loaded into the supercritical point dryer. The inset at the bottom of the figure shows the base of the holder (handle and chip cover plate removed) with $3\text{ mm} \times 3\text{ mm}$ chips in the cavities.

The third module, *dicing*, consists of several steps that are required to saw the wafer into chips ($3\text{ mm} \times 3\text{ mm}$). Each of the $3\text{ mm} \times 3\text{ mm}$ chips contains one of the sensitive design accelerometers and two of the robust design accelerometers. The processing consists of coating the wafer with photoresist which serves as a protection layer during the sawing of the wafer. The wafer is then mounted on dicing tape, sawn into die, and 24 of the die are picked from the tape. The picked die are loaded into a custom Teflon chip holder (Fig. 4) for cleaning with wet solvents and oxygen plasma. The dicing has to be done at this point in the process, prior to the release of the MEMS structures, and with the protective layer of photoresist. During the sawing, a jet of water is flowing onto the wafer, and wafer particles and

TABLE IV
DICING STEPS AND ASSOCIATED EDUCATIONAL TOPICS

| Steps | Educational topics |
|--------------------|---|
| 1. Protective coat | Must protect the MEMS structures. Sawing creates debris that could prevent the movement of the MEMS if debris is trapped in the MEMS structures. |
| 2. Sawing | Mount wafers onto the dicing tape. Operate the dicing saw. Set sawing parameters and check operation using a silicon test wafer before sawing the SOI wafer. Use tweezers to pick chips from the dicing tape. |
| 3. Cleaning | Use of the custom chip holder to place chips into solvents to remove photoresist. Importance of oxygen plasma to remove the hardened photoresist. |

TABLE V
RELEASE STEPS AND ASSOCIATED EDUCATIONAL TOPICS

| Steps | Educational topics |
|-------------------------------|--|
| 1. HF etch | Working with HF on the wetbench: procedure and safety. Characterization of the silicon dioxide etch rate in HF. Underetching of the silicon, selectivity. Requirement for holes in the seismic mass to aid in underetching. |
| 2. Supercritical point drying | Supercritical point dryer system configuration and operation. Requirement to keep the die wet prior to loading into the dryer to prevent stiction. Mechanical structures on the accelerometer are used to reduce stiction. Use of ESD wrist strap and packaging to prevent device damage after release. |
| 3. Evaluation | Verification of the silicon dioxide etch rate in HF, and comparison of the etch rate to published results; determine factors that affect the etch rate. |

other debris are released, which could damage any exposed accelerometer structures. An important point of this module is to convey the critical nature of the MEMS process sequence and packaging that are required in order to fabricate and protect the MEMS structures. Another key topic is the discussion of the differences between the MEMSlab process sequence and that of standard MEMS and IC production processes, in which the dicing is typically done after the processing and testing are completed. Table IV shows the steps and educational goals of this module.

The fourth module is *release*, which consists of an HF etch and supercritical point drying. The custom chip holder is again used for these processes. The etch rate of silicon dioxide in HF is determined by the students and compared to published etch rates. One die is etched for four, five, and six minutes, respectively. Then, the seismic mass is removed by mechanical force (using tape or tweezers), and the die are inspected using an optical microscope. Fig. 5 shows an optical microscope photo of a partially etched silicon dioxide layer (under the seismic mass which has been removed). By measuring the remaining silicon dioxide underneath the seismic mass for the different etch times, the etch rate and its linearity can be estimated. After the etch rate is determined, and the time, T , to remove all the silicon dioxide is calculated, the remaining die are loaded into the custom chip holder and etched with 30% over-etch time (i.e., $1.3T$). In this way, the silicon dioxide is removed from the areas below the seismic mass, spring cantilever beams, and comb fingers [Fig. 1(c)]. The chips (and the base of the chip holder, Fig. 4) are then loaded into the supercritical point dryer and removed after the drying sequence is completed. The custom chip holder is an important component of the process because it allows wet processing of chips. The holder can be placed into the ultrasonic bath, can keep the chips wet when the holder is taken out of a liquid during a transfer (to the critical point dryer for example), and the handle can be dismantled such that the base of the holder containing the chips can be loaded into the

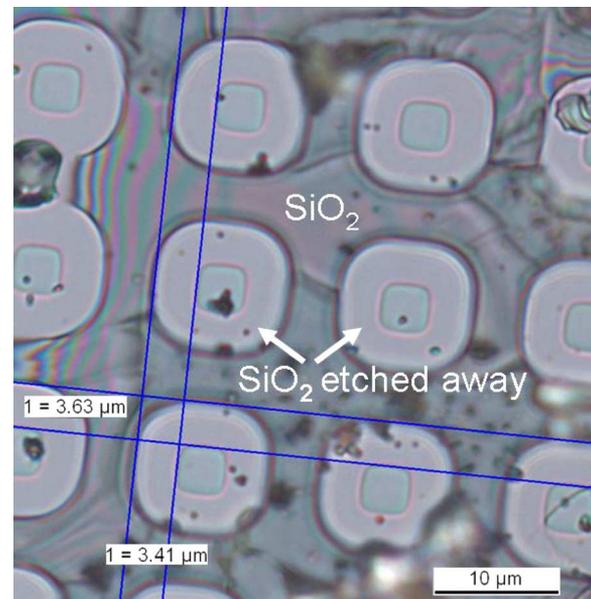


Fig. 5. Microscope image of a portion of the accelerometer die after removal of the seismic mass revealing the underlying SiO_2 layer which has been partially etched by HF.

supercritical point drying chamber. For all steps following release, an electro static discharge (ESD) wrist strap is used when handling the chips. Table V shows the steps and educational topics of the release module.

The fifth module is *packaging* and includes testing functionality of the die on a probe station, attaching functional die into dual inline packages (DIPs) with epoxy, using wedge bonding to connect the die pads to the DIP pins, and placing lids on the DIPs. Students become familiar with the operation of the probe station and electrical equipment (arbitrary function generator) used to test the die. Upon contacting the die with the probes on the probe station, a sinusoidal voltage (amplitude

TABLE VI
PACKAGING STEPS AND ASSOCIATED EDUCATIONAL TOPICS

| Steps | Educational topics |
|-------------------------------|---|
| 1. Selection of die (testing) | Probe station setup and operation. Grounding, ESD and wrist strap. Setup and operation of the arbitrary function generator. Observation of movement of the mass and comb fingers due to electrostatic force. Yield comparison between robust and sensitive accelerometer designs. |
| 2. Die attach | Selection of package and adhesive: coefficient of thermal expansion package/epoxy/silicon die, package pin count and cavity size, compatibility of package with test setup. |
| 3. Wire bonding | Operation of the bonding tool: bonding requirements to silicon die and to metal pins, bonding parameters and variables. Visual inspection of the bonds. |

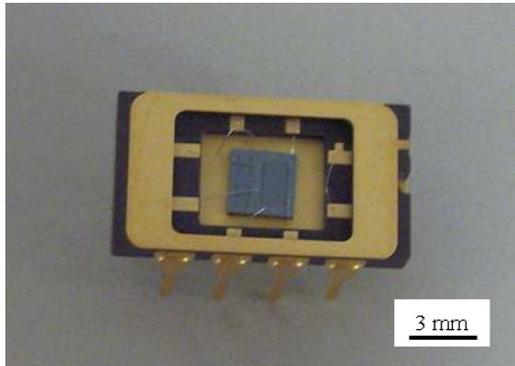


Fig. 6. Photograph showing the packaged MEMSlab accelerometer chip (without package lid).

range 1–5 V typical) at 1 Hz is applied to the accelerometer. By viewing the comb fingers of a functional accelerometer die through the microscope at low magnification ($5\times$ to $20\times$), the changing colors caused by optical interference and diffraction as the combs move can be seen [6]. At higher magnification, the motion of the individual fingers can be observed. Students learn that it is important to test the functionality prior to packaging because packaging incurs a relatively large cost (in terms of both money and time), and packaging of nonfunctional die is therefore a wasted expense [7]. Functional die are selected for packaging. An important issue in packaging is the orientation of the die in the DIP, since the orientation of the die must be consistent with the requirements of the test setup. Students are given the opportunity to make test wire bonds (wedge bond) on metal pads on ceramic blocks as preparation for bonding the accelerometers in the packages. The functional accelerometer die are then wire bonded, and lids are placed onto the DIPs to complete the packaging step. (On the accelerometer chip, aluminum wire bonds are made directly to the $5\text{-}\mu\text{m}$ -thick conductive silicon device layer: pads P1, P2, P3, P4 and Pm of Fig. 1. The pads are electrically isolated from each other by the etch trenches formed during dry etching.) A packaged die is shown in Fig. 6, and the process steps and educational topics of the packaging module are shown in Table VI.

Electrical readout is the sixth module, which consists of testing the functionality of the packaged accelerometer die using an inductance-capacitance-resistance (LCR) meter, as well as testing and understanding the functionality of the PCB (printed circuit board) that will be used in the dynamic accelerometer testing during the seventh module. During the LCR meter test, in addition to determining the base capacitance

of the accelerometer, the parasitic capacitance associated with the DIP and fixture are determined. Furthermore, the capacitance of the sensor versus bias voltage and the pull-in voltage are measured [8] for both robust and sensitive accelerometer designs. Stiction is avoided during pull-in voltage testing by mechanical stops, microtips with contact area on the order of 1 micron, on the accelerometer mass and springs. Fig. 1(b) shows the mechanical stop labeled “ms.” The steps and educational topics of the module are shown in Table VII.

The PCB used for measuring the accelerometers is shown in Fig. 7 and has two measurement chains. One chain is for the reference sensor (Analog Devices ADXL250) [9], and one chain is for the MEMSlab accelerometer [10]. The PCB with multiple ICs and discrete components (capacitors and resistors) is chosen for educational purposes instead of a single-chip capacitance measurement solution. With the multiple IC/component PCB configuration it is possible to view the AC signal propagation through the chain using a high-impedance probe and oscilloscope. In this way, students can better visualize the circuit function, signal propagation, and measurement principles [10], [11].

The final module is called *sensor characterization* and consists of measuring static 1 g acceleration due to gravity, and measuring dynamic accelerations to 10 g using a test stand. The mechanical test stand is shown in Fig. 8 and consists of a loudspeaker and the PCB, and associated measurement electronics (DC voltage supplies, arbitrary function generators, amplifier, oscilloscopes). The mechanical test stand (loudspeaker) is a simple and cost-effective laboratory setup for acceleration testing when compared to commercially available shakers. The fabricated accelerometers are plugged into the PCB which is mounted on the loudspeaker. The loudspeaker is driven with a sinusoidal signal at 60 Hz and the resulting sinusoidal analog output signal of the accelerometer measurement chains is observed on an oscilloscope. The MEMSlab sensors are characterized with acceleration up to 10 g as determined from the reference sensor (ADXL250). The measured sensitivities of the MEMSlab accelerometers are typically $\sim 2\text{ mV/g}$ and $\sim 35\text{ mV/g}$ for the robust and sensitive designs, respectively, and are, by design of the PCB measurement chain, dependent on the amplitude of the input modulation voltage [10]. The measured sensitivity of 35 mV/g is within the range of those reported by commercial manufacturers [12], [13]. Table VIII summarizes the steps and educational objectives of this module.

Within the process flow, a drawback is that there are no metallization steps or high temperature annealing steps, which are generally included in a production MEMS or IC process. It would be desirable to have these steps for educational purposes.

TABLE VII
ELECTRICAL READOUT STEPS AND ASSOCIATED EDUCATIONAL TOPICS

| Steps | Educational topics |
|----------------|--|
| 1. LCR testing | LCR meter setup and operation. Parasitic capacitances of package and sensor. Capacitance versus voltage characteristics of the sensor. Pull-in voltage. Requirement of AC signal for capacitance measurement. |
| 2. PCB testing | PCB circuit blocks, operation, and function. Operation of oscilloscope with high impedance probe, arbitrary function generator, and DC voltage supplies. Measurement of signal at various test points of the PCB. Determine the cause and magnitude of the DC offset at the output of the PCB. Adjusting the modulation voltage amplitude & frequency for optimal output signal. Noise and error contributions from the electrical readout circuit. Accelerometer capacitance measurement and comparison to LCR measurement. |

TABLE VIII
SENSOR CHARACTERIZATION STEPS AND ASSOCIATED EDUCATIONAL TOPICS

| Steps | Educational topics |
|-------------------|--|
| 1. Sensor testing | Reading specification sheets for sensors and measurement equipment and understanding contribution to measurement error. Operation of test setup (oscilloscope, arbitrary function generator, voltage supplies, amplifier). Determine accelerometer sensitivity, linearity, offset, minimum detectable signal. Determine error sources and propagation, perform error analysis. Yield & performance comparison of robust and sensitive accelerometer designs. |

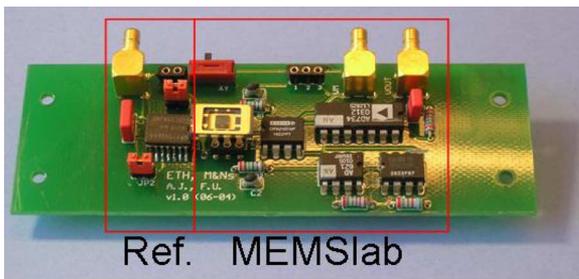


Fig. 7. The PCB used for measurement of the MEMSlab accelerometer and reference accelerometer, with the components that make up the measurement chains labeled MEMSlab and Ref, respectively. The PCB dimensions are 3.8 cm \times 12 cm.

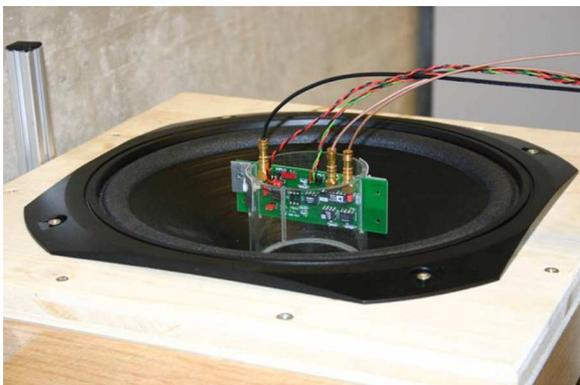


Fig. 8. The dynamic test stand (loudspeaker) with mounted PCB used for testing the acceleration to 10 g.

Instead, the process was developed to use the doped silicon layer as the conductive device layer because then enough time remains within the course schedule for the students to experience packaging. The packaging of MEMS strongly affects the

design, function, and cost [7] and is therefore included and emphasized in the course rather than introducing a metallization step. Packaging is not typically addressed in microelectronic and MEMS fabrication courses [14]–[16]. With respect to packaging, a desirable improvement would be to implement wafer-level packaging prior to the conventional die-bonding and wire-bonding [17], and this enhancement is being considered from the point of view of both process and schedule.

IV. EVALUATION

The course was evaluated by both the enrolled students (by means of a written survey and verbal comments) and by the tutors (verbal comments). Several improvements to the course were made based upon both these evaluations and the ongoing development activities for the course. A selection of the student feedback (from the written survey and verbal comments) is summarized in Table IX, and comments with respect to the feedback, or changes made to the course, are listed if applicable. In general, the students very much appreciate the opportunity to participate in the laboratory fabrication, packaging, and testing, and so the feedback has been predominantly positive. The predominantly positive feedback (students agree or strongly agree) with respect to the written survey questions include such topics as clear course organization, course content meeting expectations, introductory lectures helping in understanding practical course aspects, reasonable difficulty of daily tests, the degree to which making student presentations helps to understand the subject material, clear and understandable script content, innovative and unique course content, and a reasonable course workload for the credits received.

A significant change was made to the design of the accelerometers and the associated photolithographic mask. In the early semesters of the course, the accelerometers were designed with multiple folded springs (soft springs) which suspended the

TABLE IX
STUDENT FEEDBACK AND COMMENTS ABOUT THE FEEDBACK

| Student feedback | Comments about the feedback |
|---|--|
| 1. Tutors well prepared and knowledgeable | Until 2007, all of the tutors were directly involved in the development of the course, processes, and testing, and had knowledge of the details and subtleties involved. This experience was appreciated by the students. Maintaining this is challenging, but efforts to transfer this experience and knowledge to new tutors are ongoing by tutor-tutor training. |
| 2. Well organized and complete script | Allows students without prior lectures in semiconductor physics/processing experience to participate in the MEMSlab course. |
| 3. Daily tests useful for preparation | Based upon the feedback, on average 4 hours are spent outside of the scheduled class time per week in preparation. |
| 4. Additional testing time would be beneficial | Laboratory and test setup are available to students to use after the regularly-scheduled course time. Several groups have taken advantage of this. |
| 5. Would like to learn about the clean room equipment which is not used during the course | An overview of the clean rooms, the equipment, and the processes for which the equipment is used is included during the introductory lectures. Students are encouraged to participate in a bachelor, master, or semester project which would allow for additional clean room experience. |
| 6. Disappointed that few or no accelerometers functioned at test | Working sensors fabricated in previous semesters are available for test and characterization. Partially processed wafers are staged at several processing points in order to provide a backup if needed. Convey to students that grade is not based upon accelerometer yield, but on understanding what is done. Revised accelerometer designs and mask resulted in yield improvement. |
| 7. Electrical readout and sensor characterization is difficult for non-EE students | Script has been and continues to be updated to provide additional explanation and information in these two sections. Student groups are mixed (EE, ME, other) to let students within the group learn from each other as well as from the tutors. |
| 8. Not always clear what data should be recorded while in the laboratory | Script and run sheet have been updated to include details on the required data which should be recorded during each of the laboratory modules. |
| 9. Would like to do accelerometer design and mask layout | Not possible within the schedule for this course which focuses on the fabrication, packaging and testing. Provide design theory, method, and trade-offs in the introduction lectures and script. |
| 10. Would like to design and build the accelerometer test circuit | Laboratory and financial support available if students choose to do this as an extra project. Several students/groups have done this in the past. |

seismic mass [18]. The yield of these accelerometers was low because the springs were not stiff enough, and the seismic mass would become stuck (stiction) due to mechanical handling, ESD, or during electrical testing. Indeed, the design had a (calculated) pull-in voltage below 1 volt. Because the designs were not robust, they were not easily fabricated, packaged, or tested. This lack of robustness resulted in a situation in which students and tutors were frustrated with the end result: they had no sensors to test and were not able to compare test results to the theoretical (calculated) values. Furthermore, the lack of yield made it impossible to verify and troubleshoot the operation of the PCB MEMSlab measurement chain and test stand. In late 2005, the sensors were redesigned and a new mask was made with only two accelerometer designs, one robust design with calculated pull-in voltage of 20 V, and one sensitive design with pull-in voltage of 9 V. The minimum feature size was increased to 1.5 μm on the robust design compared to 1 μm and 1.25 μm in earlier designs. Since using the new mask, the yield has been acceptable ($\sim 75\%$), and the student groups have accelerometers to test at the end of the course. Student motivation and enthusiasm is observed to be at its highest when there are working MEMSlab accelerometers available to test.

The course provides the opportunity for students to participate in additional projects or perform additional testing. Examples of projects that students have done include the design and fabrication of several new test PCB boards and breadboards. For these projects, the students are given access to the laboratory, and the hardware (such as ICs, PCB, connectors, etc.)

is funded by the department, while the students design, document, assemble and test the boards. The test laboratory was made available for additional testing, and students took advantage of this to test the accelerometers with varying input signals (other than the standard sinusoidal signal). In fall 2006, students from the previous semesters were invited to participate in a visit to Siemens VDO to learn about the automotive accelerometer activities, to see the facility, to test the MEMSlab accelerometers on the shakers, and to characterize the mechanical resonant modes of the PCB.

The recurring cost of the materials required to run the course is about \$3200 per semester and includes the SOI and silicon wafers, the DIPs, chip trays/packages, and the printing of the script. The costs of the consumables in the clean rooms (chemicals, photoresist, etc.), and labor costs, are not accounted for in this figure.

V. CONCLUSION

A practical course has been described in which the participants fabricate, package, and test a single-axis accelerometer during seven half-day laboratory sessions. Two introductory lecture sessions are included at the beginning of the course. With the course format described here, which includes a dedicated course script, students without prior semiconductor physics or process experience can participate in the course and learn the important aspects of MEMS fabrication. The script and introductory lectures also provide information on accelerometer de-

sign, and the related requirements and limitations which the process places upon the design.

ACKNOWLEDGMENT

The authors would like to thank the persons involved in the course and process development: D. Bachmann, W. Glatz, A. Jungen, S. Schmid, B. Schoeberle, C. Stampfer, F. Umbrecht, L. Durrer, T. Helbling, S. Kuehne, M. Suter, E. Schwyter, C. Boutry, M. Muoth, M. Wendlandt, H. Sehr, J. Dual, B. Nelson, K. Vollmers, S. Blunier, B. Boser, U. Lang, and E. Koepilae. The authors would also like thank the students who enrolled and completed the MEMSlab course, and provided comments and feedback on the course as well as G. Krettler, L. Gier, and W. Herden of Siemens VDO, Schwalbach, Germany.

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