VIRTUAL TECHNOLOGY LABS – AN EFFICIENT TOOL FOR THE PREPARATION OF HANDS-ON-MEMS-COURSES IN TRAINING FOUNDRIES

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Abstract *— Hands-on-training in high technology areas is usually limited due to the high cost for lab infrastructure and equipment. One specific example is the field of MEMS, where investment and upkeep of clean rooms with microtechnology equipment is either financed by production or R&D projects greatly reducing the availability for education purposes. For efficient hands-on-courses a MEMS training foundry, currently used jointly by six higher education institutions, was established at FH Kaiserslautern. In a typical one week course, students manufacture a micromachined pressure sensor including all lithography, thin film and packaging steps. This compact and yet complete program is only possible because participants learn to use the different complex machines in advance via a Virtual Training Lab (VTL). In this paper we present the concept of the MEMS training foundry and the VTL preparation together with results from a scientific evaluation of the VTL over the last three years.*

Index Terms — Hands-on-training, Virtual Technology Lab, MEMS, education and training foundry.

INTRODUCTION

It is widely agreed that in today's highly industrialized world the main resource of developed countries lies in the know-how of scientists and engineers. A large effort is spent on keeping university curricula up-to-date to educate students in state of the art science and technology and on training through research so that students receive cutting edge experience during their university years. Also of ever increasing importance is life-long-learning, i.e. the ability to stay current with new research trends, results and techniques. Combined with the aging working population, this will result in an increasing demand in postgraduate education and training courses in the near future. At the same time, the resources available for education are limited, so that training has to be cost efficient as well as up-to-date.

In addition to well-based theoretical knowledge, it is also important in high-tech fields to provide students with practical experience in key technologies. This, however, often means large investments for equipment, which usually can not be covered through education resources alone. In most cases, high-tech equipment at universities is therefore financed through R&D projects via EU or national programs. In industry, high-tech equipment is correspondingly financed through manufacturing processes. As a direct result, the availability of high-tech equipment for training and education purposes is severely limited in both universities and industry: in addition to the time necessary for the training, the risk of damaged equipment is higher due to the inexperience of the trainees.

One exemplary field where this limitation has become very apparent in recent years in German universities is the field of Microsystems technology or MEMS (micro electro mechanical systems). MEMS is based on microtechnological processes which require a clean room and many specialized machines resulting in typical investment costs of over US$ 10 Mio. and running cost for upkeep of the clean room of close to US$ 1 Mio p.a. [1]. While this is a rather extreme example of high investment costs, many other new fields like nanotechnology or bioengineering but also classical disciplines like RF electronics or hydraulic engineering face the same principal problem: practical experience for students during their university education is very limited resulting in sub-optimal education results.

One way to address this situation is cost sharing in high tech education in what we have termed education and training foundries. The term is derived from microelectronics where a production foundry supplies the equipment and personnel which is then used by many companies to manufacture specific products, i.e. customer specific circuits (ASICs). Correspondingly, a training foundry will provide the infrastructure and personnel for state-of-the-art training courses which are then used by several universities and also industrial partners.

MEMS HANDS-ON-TRAINING FOUNDRY

MEMS is a highly interdisciplinary field with applications ranging from the automotive industry to computer engineering to medical applications and biotechnology to name only a few. The emphasis of MEMS research in universities is therefore very diverse which is evident from the integration of MEMS in curricula. While in most universities, MEMS is part of classical engineering courses, mainly electrical engineering, in some universities it is combined with special fields like optics, medical

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engineering or biotechnology. Only a few universities offer MEMS as an independent degree program covering the complete technological spectrum. For all of the different areas, however, providing an insight into the effects when entering the micro-world of MEMS is fundamental for a deeper understanding of the potential and the limitations of the technology. This experience can only be gained with hands-on-training in a clean room with modern equipment. While many universities offer lab courses to provide hands-on experience, due to the high cost of the equipment, the limited time available and the serious problems arising from equipment down-time after false operation, these “hands-on-trainings” often offer only very limited experience. Mostly, the lab courses consist of a practiced operator showing students how to operate the machines with only few students having the chance to operate the machines themselves.

Fortunately, the basic technologies used are identical for all application fields and therefore this basic hands-on-training can be performed with standard equipment and processes. In depth practical experience with these basic technologies can be gained within a rather short time. In our experience, one week hands-on-training allows students not only to learn the different process steps, but to manufacture a whole device starting from a Silicon wafer and ending with a packaged sensor ready for testing. With this complete process flow, students not only learn about the individual processes but also experience directly the interdependence of the many steps necessary for a complete device.

In order to prepare students for these training courses, a virtual technology lab (VTL) was developed which already trains the students in using the clean room equipment through computer simulations. This concept is comparable to a flight simulator used for training pilots before flying in real planes. With this preparation, students can concentrate on the processes and the results to be achieved instead of having to concentrate on using the machinery. The VTL is therefore crucial for providing in-depth experience and a deeper understanding of the technologies within a short time frame during the real hands-on-training.

As a result, a MEMS lab specializing in hands-on-training can provide in depth experience with excellent results for many students from different universities. This makes much more efficient use of existing resources than each university investing in its own clean room for basic training. Universities can instead invest their resources in specialized equipment for their research fields. The concept of the MEMS training foundry was developed over the last years within the projects INGMEDIA and pro-mst financed by the German ministry for education and research [2,3]. Currently, the pro-mst foundry at the University of Applied Sciences Kaiserslautern in Zweibrücken is used by six different higher education institutions. The University of Applied Sciences Aachen and Saarland University not only send their students to Zweibrücken on a regular basis but also cooperate in the development of the Virtual Training Lab as well as in the supervision of the training courses.

Hands-On-Training Course Pressure Sensor

A micromachined piezoresistive pressure sensor is a typical example for a MEMS device. Its function is simple and serves as a basic example in nearly every course on MEMS. Its realization requires only comparatively few process steps, see Fig. 1, but these already comprise key microtechnology steps: photolithography, thin film deposition, diffusion doping, high temperature oxidation, etch processes and bulk micromachining for the Si chip as well as anodic bonding, wafer dicing and wire bonding for packaging and assembly.

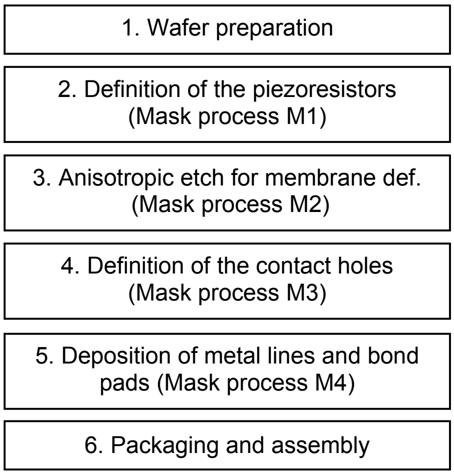

FIGURE 1
MAIN PROCESSES FOR THE REALIZATION OF A MICROMACHINED PIEZORESISTIVE PRESSURE SENSOR BASED ON SI.

However, even this seemingly simple manufacturing process is composed of over 100 different process steps [3, 4], each of which has to be performed with a high degree of accuracy to result in a functioning sensor element as shown in Fig. 2. To achieve this result within a one week course requires thorough theoretical preparation plus additional training in the machines to be used in the clean room.

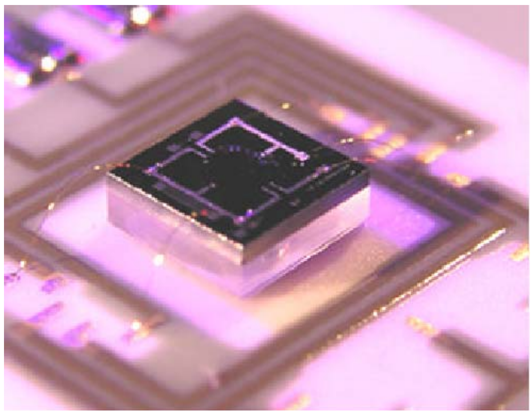

FIGURE 2
MICROMACHINED PRESSURE SENSOR MANUFACTURED IN A ONE WEEK HANDS-ON-TRAINING.

The Virtual Technology Lab

Preparation of participants for the hands-on-course is the main goal of the virtual technology lab. In addition, this allows a review of the theoretical background, i.e. MEMS process technologies, for the specific task of the course. To achieve this, the overall process flow for manufacturing a micromachined pressure sensor is reviewed and the most important machines to be used are introduced. For this simulations and/or animations are used depending on the complexity and the amount of manual handling involved. In some cases, additional videos clarify the manual handling steps involved.

In the current standard course "pressure sensor", the real lab makes use of over 20 different process tools or measurement devices, together called "machines". For the virtual lab, currently six of the most important processes have been simulated (mask alinger, spin coater, wet chemistry bench, high temperature oven, sputter coater, anodic bonder) plus two of the more complex measurement devices (film thickness probe, ellipsometer).

FIGURE 3
EXAMPLE OF A REAL MACHINE (MASK ALIGNER MA6, SUESS), TOP, AND ITS VIRTUAL EQUIVALENT, BELOW.

- **Simulations** are employed for complex machines, controlled either by computer with a GUI or a machine control panel, by programming a copy of the user interface using LabVIEW (NI) or Director (Macromedia). One example is the mask aligner shown in Fig. 3.
- **Animations** are used in those cases, where only limited interaction occurs between the machine and the user. They are used to shows the operation of the machine after the user has input the necessary data (for example for the spin coater) and also to clarify the theoretical background by using animations (for example the optical pathway in the film thickness probe).
- **Videos** are additionally used to show manual operating steps, where simulations or animations would require to much effort for the desired effect. One example is the wafer handling for the mask aligner.

The machine behavior, i.e. the result of the process performed by the machine, is modeled based on either a simplified physical model (for example, the Deal-Grove-Model [5] is used for the thermal oxidation of Si in the simulation of the high temperature oven) or on a data field obtained from the real machine and interpolated by the software (for example, the virtual sputter coater is based on the characteristics of the real sputter coater). In some cases, the data input by the user is simply checked for being within acceptable boundaries (for example, the anodic bond simulation checks for correct parameters for temperature, pressure and voltage etc.). It is important to note that for the desired better understanding and the preparation for the real lab course the physical exactness is less important than the look and feel of the simulation.

To simulate the overall process flow a virtual wafer box is used allowing the user to combine the virtual processes and achieve similar complex results as in the real lab. This wafer box as well as a virtual tool box and a virtual lab protocol are accessed via a standardized navigation tool bar

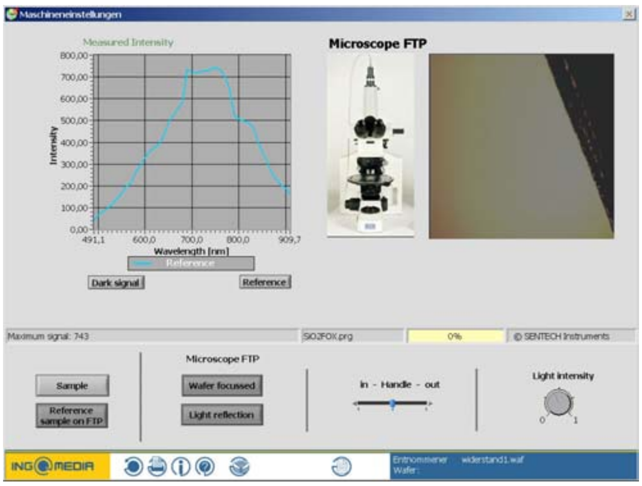

FIGURE 4
VIRTUAL MACHINE FILM THICKNESS PROBE, WINDOW "MACHINE PARAMETERS".

serving as a reference frame for most machine simulations. The tool bar also contains standard operations like printing and help function plus additional information texts to guide the user as shown in Figs. 3 and 4. The process simulation with coupling of different machines has only been started and is currently limited to the pressure sensor process flow, i.e. users cannot simulate the manufacturing process for other devices like accelerometers. The necessary simulation complexity increases considerably when arbitrary process combinations have to be taken into account. So far, it is not clear if the additional effort will lead to a corresponding increase in the learning effect for students.

The VTL is contained on a CD-ROM allowing individual training of the participants. However, experience shows that an assisted introduction into the use of the simulation is helpful and increases the willingness of participants to make use of the simulations. Additional information is contained in two books ("pressure sensor cookbook 1 and 2", in preparation), the first containing the background information on the MEMS processes themselves, the second in-depth information concerning the real and virtual laboratories.

Evaluation of the training foundry with VTL

The MEMS training courses were continuously evaluated over the last years with special emphasis being placed on the VTL to prove its effectiveness and to develop guidelines for efficient development of similar simulations. The evaluation was performed using standardized questionnaires as well as individual interviews of participants and also of the tutors.

This evaluation has shown that participants have gained considerable experience in MEMS process technologies and felt well prepared for working in a MEMS laboratory after the one week training. However, even though a complete process flow was realized, the mutual interdependence of the different processes and parameters was still limited, because the emphasis during training was placed on the individual processes. This could be improved by allowing the users more freedom to design their own processes and play with different parameters. However, variation of parameters or processes would be much too costly in the real lab. Further development of the virtual lab allowing more design freedom and complex process simulations would therefore seem a suitable approach to emphasize process and parameter dependencies for deeper understanding. This more complex VTL could be applicable for advanced users who have already gained basic experience within the current framework.

The effect of the VTL preparation was clearly visible in the ability of participants to perform the required complex tasks in the real lab as well as in the evaluation of the participants and the appraisal of the tutors. After completing the VTL, participants felt very well prepared for the real lab, table I. After completing the real lab, most stated that without the virtual preparation they would have had difficulties completing the required tasks, table II. Over the years of the evaluation this assessment grew as the VTL was gradually improved and contained a more complete machine set.

TABLE I

PREPAREDNESS THROUGH THE VIRTUAL TRAINING (ADAPTED FROM [4]).

Did you feel well prepared for the real manufacturing processes via the virtual training?						
	High-temp. oven	Mask aligner	Sputter coater	Anodic bonder	Ellipso-meter	Film Thickn. Probe
WS 03/04 1)	1,4	2,1	1,4	1,7	- 3)	1,6
WS 04/05 2)	1,2	1,3	1,2	1,1	1,1	1,1

1) on a scale of 1 ("fully agree") to 5 ("completely disagree")

2) 1 = yes, 2 = partially, 3 = no

3) The ellipsometer simulation was not yet part of the VTL in the WS 03/04.

Tutors confirmed that participants trained via the VTL generally made less operating errors which could either lead to wrong results or, even worse, damage the machines. They also stated that questions asked during the real lab where less focused on the machine operation and showed a deeper understanding of the processes.

For efficient development of the simulation tools it was very important that the developers were familiar with the basic technologies and also the real lab course. I.e., in our experience it is extremely important to have engineers with a solid background in the topic of the course to give feedback to the computer scientists with their special programming skills. The optimal situation would be to have developers experienced in both worlds, i.e. programming and MEMS. For the continuous improvement of the virtual machines, tutoring the virtual lab as well as the real lab proved to be the most efficient way to receive user feedback.

Overall, the virtual technology lab has to be complemented with additional support material covering the basic theoretical know-how required. This can generally be in the form of a basic text book on the subject, but a more specific collection of material selected for the topic of the lab will help participants to find the required information faster. The division of this additional material in one process and one machine specific collection also helped with the orientation. Compact summaries or introductions providing at a glance an overview over the complete process or system have proven very helpful for getting started and for understanding the relationship between the different sub-processes or parts.

TABLE II

INFLUENCE OF THE VIRTUAL PREPARATION ON SUCCESSFUL COMPLETION OF THE MEMS HANDS-ON-TRAINING COURSE (ADAPTED FROM [4]).

Would you have been able to successfully complete the clean room lab considering the realized tasks and support without the virtual training up front?						
	High-temp. oven	Mask aligner	Sputter coater	Anodic bonder	Ellipso-meter	Film Thickn. Probe
WS 03/04	2,0	2,0	1,8	1,8	-	2,0
WS 04/05	2,5	2,6	2,1	2,1	2,5	2,4

1 = yes, 2 = partially, 3 = no

Also, preparation of short presentations on specific topics for the virtual lab tutorials by the participants themselves was helpful for achieving a deeper understanding.

CONCLUSION AND OUTLOOK

Three years experience with the MEMS training foundry and evaluation of the Virtual Technology Lab in its frame has resulted in several clear indications for improving education in high technology field:

- While theoretical knowledge forms the basis, hands-on-experience is important for an in-depth understanding of complex technological processes.
- Real hands-on experience is achieved within a comparatively short time frame if students can concentrate on the content instead of learning basic machine operation.
- Virtual training can provide sufficient basic knowledge of machine operation even with comparatively simple simulations off the functions and processes within.
- A blended learning concept, composed of computer simulations allowing self-training combined with tutorial support seems the most efficient way for teaching the necessary basics.
- While the effort necessary to develop the simulation tools and user support for a virtual technology lab is quite extensive, this effort is justified if students from not one but several universities can profit from it.

Based on our experience a training foundry is an efficient way for providing high quality practical experience in high-tech areas in general. Virtual labs complementing the hands-on experience minimize the necessary time spent in the real laboratory further reducing the cost of this training. One off the main remaining problems is financing of this type of cooperation between universities. The cost for sending students regularly to a training foundry is too high to be covered within the frame of existing education budgets. In addition, there is always the conflict between investing existing budgets at home and spending it on training elsewhere. Even though overall costs are lower, there is no financing instrument available today to establish continuous cooperations between universities in training foundries because todays support programs mainly focus on research projects or on financing infrastructure for research and training. One possible solution would be the establishment of new support programs to fund the participation of students from one university in an already established training foundry, financed nationally or even internationally, i.e. be the EU.

In the future, we plan to make additional use of the combination of hands-on-training and virtual preparation by offering post-graduate professional training courses. For industrial employees, the time spent away from work during training is one of the main cost factors in any training. Therefore, minimizing the time spent in the real lab at the training institution reduces the overall cost in two ways by reducing the cost for the lab and the cost for being away from work.

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