S. Büttgenbach / U. Hansen / H.-J. Franke / C. Germer

CAD Environment for Silicon Micromachining

INTRODUCTION

In contrast to conventional mechanical engineering there is a strong dependence of the design of silicon micro mechanical devices on the production technology. This has significant impact on the device geometries, materials and appropriate fabrication processes, since a great number of constraints has to be taken into account. In the course of the product design the definition of the layout and the specification of the processing sequence have to be considered simultaneously typically resulting in many iterative redesigns. Thus, there is an increasing demand for CAD tools which support the rapid design of complex micro components. In this paper we present a CAD environment implemented for wet chemical etching of silicon, which is one of the key technologies of micromachining.

SILICON MICROMACHINING

A silicon micro mechanical device is fabricated using a combination of lithography-based bulk and surface structuring processes carried out successively [1]. Several constraints due to incompatibilities of materials and processes have to be considered while defining such a manufacturing sequence. In order to assure its practicability the processing sequence has to be checked for consistency. Some examples for process incompatibilities are illustrated in figure 1.

The possible constraints can be grouped into three classes. First, the properties of materials or functional elements may be affected by succeeding processes. Examples are the twisting or even destruction of delicate mechanical structures due to thermally induced mechanical stress, the attack of thin film materials by a subsequent etch process, or the spreading of diffusion profiles by successive high-temperature processes. Solutions to these problems might be the use of alternative materials, the insertion of an additive process for the creation of a protective coating, and the rearrangement of the process sequence, respectively.

A second kind of incompatibilities occur, if the properties of materials or the geometry of the device processed so far have a negative influence on the quality of succeeding technology steps. Examples are insufficient adhesion of adjacent thin film layers or inadequate planarity of layers deposited on top of 3D microstructures. These problems might be solved by the deposition of special adhesive layers and the application of appropriate planarization materials, respectively. In addition, chemical residuals caused by preceding processes may affect subsequent technology steps. Such problems will be solved by inserting an appropriate cleaning step.

For these reasons there is a strong need for an automated tool that evaluates the compatibility of the defined processing sequence. This has already been pointed out by other groups, which presented tools for the validation of processing sequences for the LIGA technique [2] and for the assembly of micro components [3].

The third kind of constraints is the feasibility of generating the intended device geometry using the specified fabrication processes. This point is directly related to one of the major difficulties of wet chemical etching of silicon, namely to generate etch masks, which provide a correct transformation
of the 2D layout into the appropriate 3D structure. The problem arises from the circumstance that convex corners of the etch mask will be under-etched due to fast etching crystal planes developing at convex mask corners (figure 2a). A technique widely used to obtain well-defined shapes is the application of mask compensation structures. Well-defined corners emerge from compensating elements, which are removed along the etch limiting crystal planes (figure 2b). At a certain etch depth the additional mask element is completely under-etched. For simple geometries design rules support the proper dimensioning of compensation structures [4]. However, for 3D shapes in which rigorous design restrictions exist or complex mask layouts have to be derived, for example space limitations for compensation structures or double-sided processing of substrates, the layout procedure evolves into a time- and cost-consuming process based on trial-and-error. Hence, the integration of a tool into the CAD environment that automatically derives the layout from a proposed 3D device description has an extremely valuable effect on the design process.

Fig. 1: Examples for process incompatibilities

![Fig. 1: Examples for process incompatibilities](image)

Fig. 2: SEM micrographs of etch results at convex mask corners
(a) without mask compensation and (b) with a beam-like compensation structure

THE CAD ENVIRONMENT
In the following we illustrate the structure of the CAD environment BICEPS [5], which is being developed as part of the Collaborative Research Center ‘Design and Fabrication of Active Microsystems’ at the Technical University of Braunschweig. Special emphasis is laid on the tools for mask layout synthesis and validation of processing sequences.

BICEPS is based on a workflow system [6], which integrates the appropriate software tools and provides an overall mechanism for the common structure of a given design task as well as the flow of information inside BICEPS (figure 3). A commercial CAD software (AutoCAD) is used to create a 3D reference model resembling the intended silicon geometry. Its functional properties can be checked against given specifications using an FEM software (ANSYS). In most cases the reference model will need some modification and again further analysis until an optimal design is found. Having achieved this, the mask layout for the etch process is generated by the tool OMEA [7]. The final mask design is verified using the etch simulator SUZANA [8] to reveal the resulting 3D structure, and again finite element analysis is carried out to make sure its functional properties are as requested.

By accessing the attached central project database available at any point in the flow of work data of already completed projects can be imported into the current work. As a further extension of the work flow a tool for rule based validation of processing sequences is being developed.

**MASK LAYOUT SYNTHESIS**

The computer program OMEA determines an optimal mask layout for wet chemical etching from the 3D device description of the silicon component. The implemented technique uses a 2D genetic algorithm (GA) for searching in the design space of mask layouts. Its basic outline is shown in figure 4. Inside the main iteration an individual, represented by a mask layout set of an etch process description, is manipulated in the manner of a DNA string evolving over generations. The GA control module is coupled to the etch simulator SUZANA, which performs the underlying structuring process using a cellular automata model.

To increase the evolvement speed of optimal solutions a parallel virtual machine is used represented by a PC-cluster, which may be spread over the internet. Set up in a Master-Slave-configuration the master host works as the user interface and algorithmic control instance while the dynamically expandable slave-cluster performs the time-critical simulation tasks.
A similar approach, which treats the mask layouts as simple 2D polygons, has been reported by a group from the California Institute of Technology [9]. The approach presented in this paper, which is based on 2D bitmap descriptions of the mask layouts, offers higher flexibility and is capable of treating nearly any mask geometry. The higher overall time consumption is expected to become negligible due to future computer developments.

To demonstrate a typical design process the development of a micromachined spring actuator shall be outlined shortly. The silicon structure consists of two couplings suspended from two flexible spring elements (figure 5). Sealed on top and bottom side the structure is deflected by compressed air. In a preliminary design step the number of critical regions of the proposed structure, which have to be included into the GA procedure, can be reduced to five. Figure 6 shows part of the mask layout for top and bottom wafer side derived from the optimization process, figure 7 presents an SEM micrograph of the fabricated spring actuator.

**RULE BASED VALIDATION OF PROCESSING SEQUENCES**

The validation of processing sequences is highly dependent on expert knowledge about the manufacturing processes and materials used. Therefore, the tool is connected to databases, which contain the description of fabrication processes, materials and process media using an appropriate data model [10].

In order to check a process sequence automatically for incompatibilities, correlations between processes, materials and media have to be evaluated. These may be manifold, since a multitude of combinations are possible. Therefore, instead of simply setting up tables stating ‘compatible: yes / no’, a more generic description of the compatibility requirements is desirable. An inference engine is used for the identification of errors in the processing sequence. It is applied to evaluate the suitability of a configuration using simple rules to provide the algorithm with the needed information on possible incompatibilities. The tool presented here uses a commercially available inference engine.
The rules are expressed in an IF-THEN style, stating what action has to take place, if a certain condition is met. For example, a processing sequence as illustrated schematically in figure 1a might produce a warning “etch selectivity of exposed material silicon dioxide critical”. The etch selectivity is a value, which needs to be calculated for all exposed materials of the device and checked against a user defined value for being accepted or not accepted. The rule that fires this warning needs information about which materials should be etched and which serve as passivation. A straightforward definition of the chosen process / material configurations as well as of the whole processing sequence is offered by a graphical user interface. Figure 8 shows the relationship between the individual parts of the system [12].

CONCLUSION AND OUTLOOK

The CAD environment BICEPS has been presented, which provides a structured methodology for the design and optimization of micromachined silicon devices. The design process is controlled by a workflow system, which is used to implement co-operative working techniques and to investigate the advantages of defining domain-specific design processes. The environment contains a mask layout synthesis tool based on a 2D genetic algorithm to derive an optimal process description for wet chemical etching of silicon from a 3D device model. A tool for rule based validation of processing sequences will be integrated as a further extension to the CAD environment. Because of its modularity the CAD environment can easily be extended to other domain-specific design processes. The present workflow can be viewed as a sub-workflow in a much larger system, which integrates simulation, optimization and analysis tools for different technologies used for the manufacturing of microsystems.

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References:

Authors:
Prof. Dr. Stephanus Büttgenbach
Dipl.-Ing. Ulli Hansen
Institute for Microtechnology
Prof. Dr.-Ing. Hans-Joachim Franke
Dipl.-Phys. Christoph Germer
Institute for Engineering Design
Technical University of Braunschweig
D-38106 Braunschweig
Phone: +49-531-391-3320
Fax: +49-531-391-8101
E-mail: s.buettgenbach@tu-bs.de