Analysis and Verification of Processing Sequences

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ABSTRACT

This paper presents a rule-based software tool developed to assist with the definition and verification of processing sequences. Insight is given on the requirements needed to phrase the rules and how they can be classified. It is shown, how generics play an important role in order to increase the flexibility of the defined rules. The strategy which controls the execution of the rules is explained and the limitations of the concept are pointed out.

The usage and usefulness of the presented software is illustrated by an example showing the fabrication of a micro coil.

Keywords: process sequence, rule-based validation, process compatibility, T-CAD

1 INTRODUCTION

In the field of Microtechnology substantial research activities are in progress. New technologies are being developed and employed to generate increasingly complex microsystems. In contrast to general mechanical engineering the different micro technologies may each only be used for processing a very limited number of materials. Furthermore typically only rather simple geometries are feasible. For the majority of structuring technologies the choice of materials used is an important issue, since only the intended material should be structured and not the others present in the device. High vacuum or high temperature processes may have an impact on the treated device and consequently on its functional properties; passivation effects of metals or unwanted reactions in other processing may ruin the device before its completion.

Due to this, engineers have to be familiar with considerable knowledge about the different technologies in order to define an accurate processing sequence flawlessly. In practice, errors (in the following also called incompatibilities) will be found and corrected while iteratively trying to build the first prototypes slowing down the overall development process.

2 VALIDATION

Attempts have been made to facilitate this part of the device development using inference based computer software. The main concept is to formulate the incompatibilities between the processing and the materials used as rules. In this manner rules might simply state direct incompatibilities, e.g. that a certain resist may not serve as a masking layer in a wet chemical etching process, or that a thermal oxidation should always be preceded by a cleaning step. Such an approach is described by Hahn et al. [1,2].

In order to increase the flexibility of a rule model, rules need to be defined more universally. Referring to the example given above, the rule should not directly state the incompatibility of etch processing and resist, but do a calculation of the etch selectivities of all the eligible materials. Based on these estimations the rule may decide to have found an incompatibility, give a warning if critical values are about to be exceeded or return without complaints.

The following section describes, how this is achieved by the computer software being developed at our Institute.

2.1 Required Data

In order to evaluate a process sequence and its single fabrication steps, detailed information on the processing is essential. As stated in earlier papers [3,4], the needed specifics can be obtained from a database. Briefly summarized, the data model allows for each fabrication step to hold information on the used technologies as well as the material and geometric properties of the micro device (prior and after the processing). Each fabrication process possesses information on its settings and category plus a summary on the usable media and the machinable materials - both media and materials being equipped with a set of parameters defining their properties.

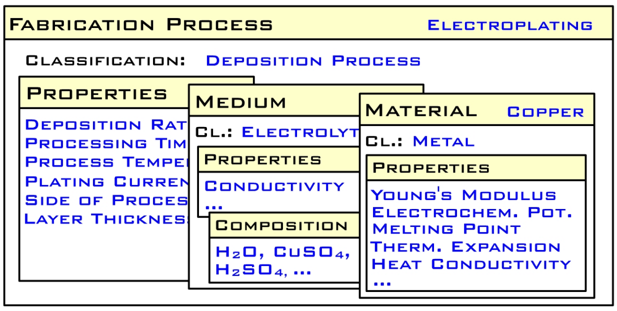

Figure 1: Example of database contents.

This concept has been enhanced in order to regard the composition of the media and changes to the material properties due to processing. Additionally so-called ‘dependent parameters' have been introduced, which allow a dynamic calculation of properties. They permit the modeling of dependencies between process, medium and/or material parameters and can be used for determining e.g. the depth of an etched hole (processing time x etch rate) or the layer thickness of a resist in a spin-on process (using spin-on constants from a database table). Figure 1 gives an overview on the information provided for electroplating. The information may be altered or enhanced by the user.

2.2 Validity of Rules

Not all rules that are needed for evaluating a process sequence apply to all fabrication steps. Commonly each processing technology has need for its own closely adapted set of rules. However, there are rules, which can be employed more generally, pertaining to similar technologies or even all processes applicable. This classification subdivides the rule-set into 'process-class rules', 'process specific rules' and 'general rules'.

A general rule is e.g. a rule evaluating the impact of the processing temperature on the materials present in the micro device. Even though many processes operate close to room temperature and no impact is expected, this has to be verified for every single step. Depending on the height of temperature and the device composition effects like critical stress between adjoining material layers, the destruction of the material (e.g. photo resist above 100°C) or smearing of dotations might occur.

When depositing a material on the micro device, it has to be assured, that the adhesion of the deposited material on the device surface is sufficient. Since this constraint is relevant for all deposition technologies - whether a metal is sputtered in high vacuum or a photo resist is spun on using a pipette - it is a process-class rule.

Process specific rules apply only to individual technologies. E.g. in electroplating a reaction between the electrolyte and the electrodes takes place due to an applied current leading to the deposition of the anode metal. However, also unwanted reactions can occur, if the electrolyte reacts with other materials present in the device. For instance the electrolyte for the electroplating of copper also contains sulphuric acid (H_2SO_4), which would react with aluminum if present and exposed in the device. A rule surveying this coherency is only useful for electroplating technology.

2.3 Generics

In order to meet the high aim of being capable to evaluate a multitude of technology and material combinations, the rules need to be phrased to be generally applicable. This opposes the rule concept introduced by Hahn et al. [1,2], which focuses on stating explicit incompatibilities between certain technology/technology or technology/material combinations. The limitations of this method become evident, whenever new materials or technologies are added to the system and the rules need to be rephrased to regard the new data.

Our software takes a different approach in calculating critical values to obtain the information to decide on, whether an incompatibility is detected or not. The already mentioned 'temperature-rule' for instance relies on the evaluation of the processing temperature and the properties of the materials (Young's modulus, thermal expansion coefficient, melting temperature, etc.). The benefit of this concept is obvious: for every newly added material, the rule still applies and changes to it are unnecessary. All material data must simply be equipped with the needed properties for evaluation.

A more complex example of a generic rule is the already mentioned evaluation, if a material of the device might react with the electrolyte while electroplating. Given the composition of the device and the electrolyte this can be calculated for all exposed materials using the Nernst equation [5]:

$$E = E^\circ + \frac{RT}{zF} \cdot \ln \frac{[Ox]}{[Rd]} \qquad (1)$$

with E° as the standard potential of the material, R the gas constant, T the process temperature, z the number of electrons involved in the reaction and F the Faraday constant. $[Ox]$ and $[Rd]$ are the concentrations (or activities for not ideal solutions) of the oxidant and reductant. A typical electrolyte for the electroplating of copper consists among other ingredients of water, copper sulfate ($CuSO_4$) and sulphuric acid (H_2SO_4). Assuming the device contains an aluminum layer and knowing the concentrations of the ions (Cu^{2+}, H^+) the Nernst equation can be evaluated:

$Al / CuSO_4$	Al / H_2SO_4
$2Al \rightarrow 2Al^{+3} + 6e^-$	$2Al \rightarrow 2Al^{+3} + 6e^-$
$3Cu^{+2} + 6e^- \rightarrow 3Cu$	$6H^+ + 6e^- \rightarrow 3H_2$
E = -1,92 V	E = - 1,60 V

The negative voltages indicate, that in both cases aluminum will react with parts of the electrolyte.

However, phrasing a rule generically is not always possible. Some incompatibilities to be checked can not be expressed in an analytical way. In fact, it would rather take specialized simulation tools to check some of these constraints, so less generic concepts have to be considered. In the case of the adhesion of deposited materials, the factors influencing the adhesion are not known well enough to allow an analytical description of the problem. Due to testing methods a relative value for the quality of adhesion may be formulated for specified material combinations and this information accessed in the form of tables. This, of course, lacks the generics described above, but is the only way to handle the task in this matter.

There are also cases, in which a possible incompatibility cannot be phrased as a rule at all. For example the impact of high temperatures on a multi-layered buildup would need FEM-analysis to examine, whether certain structures might be damaged or the function of the device is endangered [6]. This is too complex to be phrased in a rule and needs additional software to be solved. We tackle this by using a simplified description of the matter in order to be able to output a warning, which advises further checking by the user.

2.4 Rule Interactions

To allow a fast evaluation of the process sequence given, rules need to be kept as simple as possible. The act of fabricating a micro device, however, is a complex task with many interdependencies between the chosen technologies. This becomes evident in a rather fundamental segment of fabrication: the lithographic processing. Depending on the resist used, different treatment and additional processing may become necessary. Certain resist are in need of supplementary heating or conditioning steps, which might occur anywhere in the sequence. Rules checking the exposure or development steps of these resists need the information, whether this extra processing has been carried out yet. For this purpose they must be able to call other rules or use the results of already executed ones.

2.5 Execution strategy

In a first version of this software an inference engine was employed for firing the appropriate rules to each fabrication step. With a growing number of rules and larger sequences, however, it has become apparent, that this concept has too much overhead in memory consumption and becomes increasingly difficult to supervise. For verifying a process sequence it seems a more straightforward approach to check every single step individually in the order they were defined, thus emulating the execution of the sequence. The algorithm controlling this was coded and the use of the commercial inference engine abandoned.

By default all rules available are taken into account while checking the process sequence. However, the user may choose to deactivate certain rules generally or on certain processes, if he is of the opinion that this rule does not apply to his application. Additionally, the critical values used for evaluating the rules - like e.g. the minimum etch selectivity - may be altered by the user.

2.6 Limitations

Our software works with a simplified geometric representation of the manufactured device. It contains all components present in the device along with layer thickness and structured regions. This representation is analogous to the representation known from printed process plans (e.g. see fig. 2) and does only contain relative information on the lateral dimensions of the components. Therefore calculations needing the exact geometric details are not possible.

Another drawback was already mentioned in the section on generics. If the scope of the rule cannot be described analytically, a less generic and accurate implementation must be chosen. In some cases the user can only be adverted to this problem and may have to review the possible incompatibility using a different tool specialized for this task.

3 EXAMPLE

Many modern micro sensors and actuators employ micro coils with a multilayer build-up and the incorporation of magnetic structures. The fabrication of magnetic microsystems typically includes the successive steps of lithography, electroplating and dielectric passivation. Possible areas of use are the realization of electronic filters, inductive sensors and cordless transmission. In the scope of our research activities (see acknowledgement) micro coils are used for powering a linear actuator [7,8].

A typical process sequence for the construction of a micro coil is briefly summarized in figure 2. A starting layer for the electro plating of the coil is deposited on the substrate using physical vapor deposition. The shape of the coil is specified by a photo resist being structured with lithographic processing. After the fabrication of the coil layer the resist is stripped, the starting layer structured and the coil layer filled with insulation material. To add a layer to the coil this processing is repeated in a similar way, insuring that both layers are connected by a via-contact.

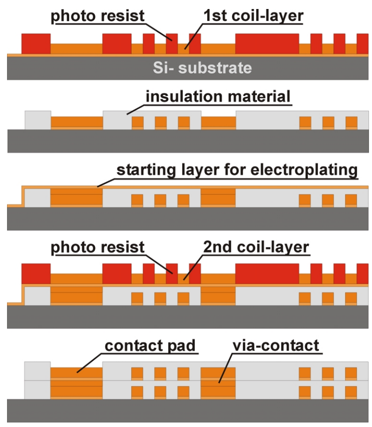

Figure 2: Process sequence for a two-layered micro coil [6].

In order to inspect the needed process sequence it needs to be defined using our software (see fig. 3). The list on the right hand side represents the sequence. Single fabrication steps are be characterized using the tabs on the left. Process definitions may be loaded from the database and modified in their properties, deployed media and machinable materials. According to each step a prediction of the (simplified) device geometry prior and after the processing is displayed below these tabs.

As the figure shows, the example of the fabrication of the micro coil has been drafted rather elementarily: after a general cleaning of the substrate a copper starting layer for electroplating is deposited. Then a resist is spun on, exposed and developed and subsequently the electroplating of the first coil layer is defined. The process parameter ‘layer thickness’ is an example for a dependent parameter, since it is calculated from the deposition rate and the processing time. Further steps of the sequence are not visible in the figure.

After defining the process sequence as intended by the engineer the verification can take place. The rule checking algorithm considers every step defined in succession. In the example shown the adhesion of copper on the silicon substrate is evaluated to be too low and an error is generated. Furthermore the tool warns of a possible passivation of the copper if exposed to the air too long. In step #3 the adhesion cannot be evaluated, because of missing data in the database. This demonstrates the drawback of rule definitions, which are not generic - as explained in section 2.3. Furthermore two errors are displayed for the following steps concerning the lithographic processing. An interesting flaw is found in the electroplating step, since the thickness of the resist used as a galvanic form is not sufficient. According to the rule, the structure height should be at least 1.5 times the intended thickness of the electroplated layer.

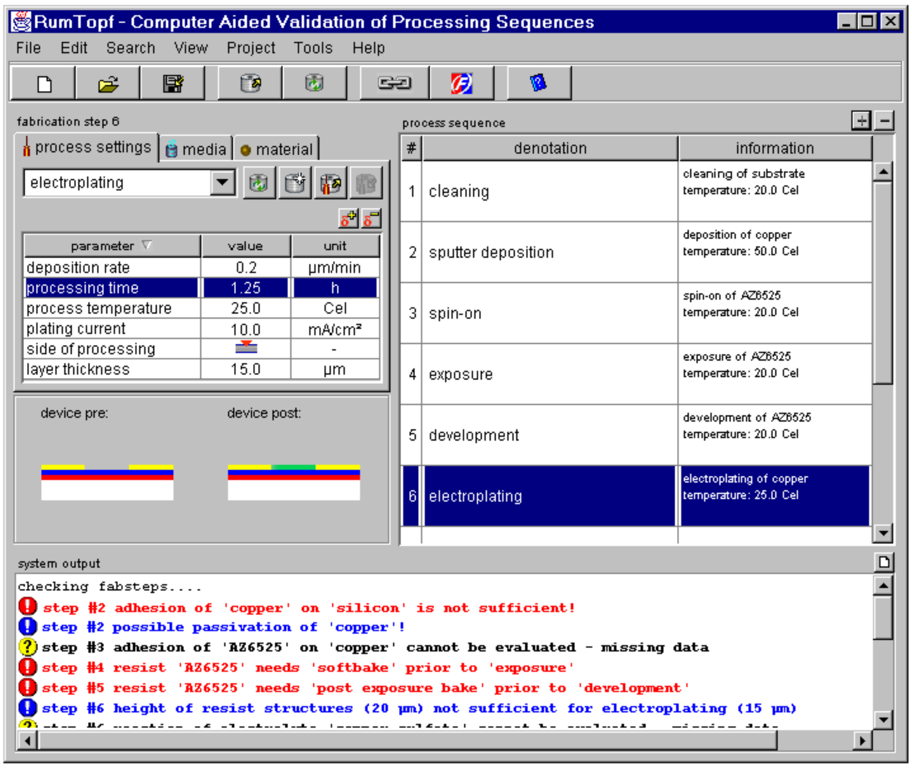

Figure 3: Screenshot of the verification tool.

This example was taken from a sequence already employed in practice, which was just simplified. The errors found emphasize the usefulness of the tool. Even though the displayed errors and warnings can easily be avoided by adding additional processing or modifying the defined, these are exactly the kind of mistakes, that are made when first defining a processing sequence. By this means the tool can compensate missing experience and expert knowledge on the part of the designer.

4 SUMMARY AND PERSPECTIVE

A rule-based software for the evaluation of process sequences has been presented. Details on the implementation of the rules and their execution as well as the limitations of the shown concept have been disclosed. Particular attention was given to the usage of generally applicable rules. The example of a fabrication sequence for a micro coil was cited as an example to show the usage and usefulness of the presented tool.

Future work will include the definition of interfaces between the presented software and other more specialized simulation tools. The aim is to facilitate the checking of constraints, which are outside the scope of the available rules. Needless to say, the tool will be enhanced with further process specific rules for additional technologies.

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