A CAD/CAM approach for layer-based FIB processing

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Abstract

The realization of complex three-dimensional structures at micro- and nano-meter scale in various materials is of great importance for a number of micromechanical, microoptical and microelectronic applications. Focused Ion Beam (FIB) patterning is one of the promising technologies for producing such 3D structures utilizing layer-by-layer fabrication methods. A novel and efficient data preparation approach is proposed in this paper for layer-based FIB processing. By applying it, complex surfaces can be designed easily in any 3D CAD package and then converted into GDSII streams for FIB sputtering or deposition. To validate the proposed CAD/CAM approach an experimental study was conducted. The factors that can affect the accuracy of the structures produced by layer-based FIB processing are also discussed. By assessing all stages of the proposed approach and the results of its experimental validation, conclusions are drawn about its applicability.

Keywords: layer-based manufacturing, CAD/CAM systems, focus ion beam machining, FIB, grey scale lithography, 3D nano and micro structuring, FIB-CVD

1. Introduction

The realization of complex three-dimensional (3D) structures at micro- and nano-meter scale in various materials is of great importance for a number of micromechanical, microoptical and microelectronic applications. Especially, this is of importantance for achieving functional integration in new and emerging products, such as biosensors, organic micro/nano-photonic systems and point-of-care diagnostic devices.

Different lithographic techniques have been utilized to fabricate complex 3D structures, e.g. grey tone photolithography [1], electron beam lithography (EBL) [2], two photon lithography [3], X-ray lithography [4], laser beam lithography [5] and nano-imprint lithography [6]. By employing these techniques, complex 3D shapes can be fabricated in resists. Subsequent pattern transfer from the structured resist to a wafer is performed via a dry etching process, such as ion milling, chemically assisted ion-beam-etching or reactive ion etching (RIE) [7]. An alternative technique is to use the patterned resist as a sacrificial template for producing metallic 3D masters through electroforming for serial replication by thermal imprinting/embossing or injection moulding [8].

Focused Ion Beam (FIB) technology offers other possibilities for performing 3D micro- and nano-structuring of almost any materials. This technology has attracted the attention of researchers due to its high patterning flexibility and sub 50 nm-resolution [9]. Furthermore, for FIB, micro- and nano- structuring of different materials is possible, without going through any intermediate stages associated with the other approaches. However, FIB milling is inherently slower in comparison to parallel beam systems such as ion projection machines. To address this deficiency, a multi ion beam concept was recently proposed that combines the high resolution capabilities of the FIB technology with the throughput advantage of the parallel lithography systems [10]. To develop this multi ion beam technology further and satisfy the requirements for high productivity, a Projection Mask-Less nano-Patterning (PMLP) system is currently under development within a European FP6 integrated project “Charged Particle Nanotech” (CHARPAN) [11]. The main component of this system is an ion optical column that comprises a plasma ion source, a condenser system to form a parallel broad charged particle beam, a programmable aperture plate to structure the beam, and a 200x reduction ion beam optics module to reduce the shaped beam; such a column will generate a high resolution and high intensity charged particle beam. By utilizing this multi-beam system together with the data preparation technique proposed in this paper, it will be possible to produce complex 3D surface structures with nanometer precision relatively fast, and at much lower costs than would be possible utilizing *other* lithography techniques [12].

To perform 3D patterning with FIB and PMLP, it is necessary to create a seamless data flow between the CAD design packages used to create 3D models and the control systems employed by these tools for producing complex 3D structures. Such CAD/CAM tools should satisfy the stringent requirements towards the geometric and dimensional accuracy of such 3D structures imposed by various applications; for example the fabrication of arrays of diffractive and refractive optical elements [13]. Another important requirement is that these tools should be compatible with data formats such as GDSII and Gerber, which are widely utilized by microelectronic industry.

In this paper, a novel approach for fabricating complex 3D structures with FIB is proposed that employs data generated by a 3D CAD package. FIB structuring of convex and concave lenses is used to demonstrate and validate the applicability of this approach for fabricating 3D micro- and nano- structures. Several factors affecting the accuracy of the fabricated structures are also discussed. By assessing all stages of the proposed approach and the results of its experimental validation, conclusions are drawn about the applicability of this method.

2. Proposed approach

FIB patterning is an appropriate technology for producing complex 3D micro- and nano- structures utilizing layer-by-layer fabrication methods. Most conventional FIB systems can handle bitmap data that define the cross-sections of single layers. However, in order to produce a complex 3D structure the generation of a stack of layers is necessary, in many cases containing tens or even hundreds of layers. Thus, it would be impractical to design and import manually the bitmap file required for producing each layer. One possible way to address this issue is to convert the graphical design data stored in a 3D CAD model into a GDSII stream file format, which can be used directly to control the FIB process. Another important advantage of such an approach is that this data exchange format is considered as an industry standard in microelectronics, where it is commonly used for electron beam lithography, and can be handled by any lithography tool software. It is worth noting that the cross-sectional geometric data associated with each layer can be created in GDSII format directly, however the preparation of GDSII data for complex 3D shapes will be very time consuming and even impractical if the model consists of many layers.

The CAD/CAM approach for 3D data preparation proposed in this paper is outlined in Figure 1. In particular, it includes the following steps:

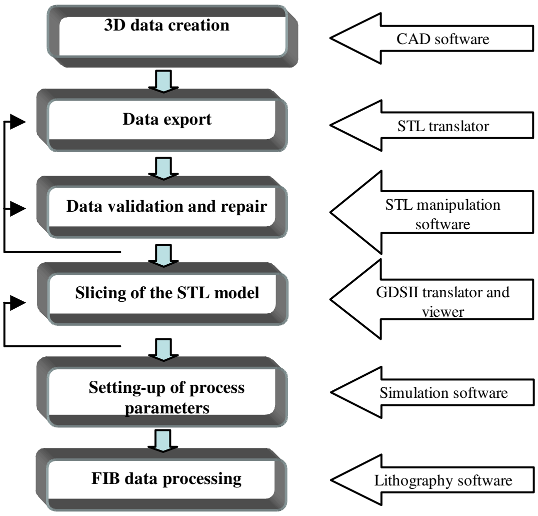

Fig. 1 The key steps of the proposed CAD/CAM method for layer-based FIB processing

2.1. 3D data creation

A CAD package, e.g. SolidWorks or ProEngineer, can be employed to create three-dimensional, unique and complete representations of micro- and nano-structures. The resulting data must be represented in a model whose surfaces define a closed 3D volume without any holes, surfaces with zero-thickness or more than two surfaces meeting along common edges.

2.2. Data Export

The valid 3D model has to be exported from the CAD package into a suitable format for CAM downstream applications. Using indirect translators, the data are exported in a neutral database structure. The STereoLithography (STL) neutral file format has been selected for exporting geometrical data from CAD packages because of its acceptance as an industry standard data exchange format for layer-based manufacturing. Currently, STL translators are available for almost all commercially available 3D modeling systems, and it is also used as an input data format by nearly all "layer-by-layer" manufacturing systems due to the file's simplicity, and software and machine independency. This format approximates the surfaces of a 3D model as a mesh of triangles and it is possible in some CAD packages to control the size of the generated file by increasing or reducing the model resolution. STL files may be in ASCII or binary format, although the latter is far more common due to its reduced file size in comparison to the ASCII format.

2.3. Data Validation and Repair

The exported data-set is an approximation of the internal precise 3D model. During this approximation process the model surfaces are represented with simple geometrical entities in the form of triangles. Unfortunately, STL models created in this way can contain undesirable geometrical errors such as holes and overlapping areas along surface boundaries. Therefore, the files generated using the STL translators have to be validated before any further processing. Some CAM packages for layer-based manufacturing offer facilities for automatic and manual model repair. They include software modules for evaluating the STL models, and determining whether any triangles are missing. In case of errors, the gaps in the models are filled with new triangles. In the CAD/CAM approach proposed here, Magics RP [14], a STL manipulation software, is employed for data validation and, if required, for repair of the STL model.

2.4. Slicing of the STL model

The 3D model in STL format has to be sliced in order to produce successive cross-sectional layers as schematically shown in Fig 2. In each cross section, poly-lines are used to approximate the exterior and interior boundaries of the RP models. Then, these poly-line boundaries can be offset by a particular value to compensate for process errors. It would have been advantageous to adopt one of the existing formats for conventional layer-based manufacturing to store the stack of layers generated in this way; however, none of them is compatible with available lithography systems, such as Elphy Quantum, and thus cannot be utilized for FIB processing. Therefore, in the proposed CAD/CAM approach for layer-by-layer FIB sputtering and deposition, recently developed software by Artwork Conversion Software Inc. [15] is employed for slicing off-line the STL models, and simultaneously for translating the sliced data into a GDSII stream. In particular, with this software the 3D model in STL format can be sliced in up to 1023 layers. After the translation, a file in the GDSII format is created that contains the same number of layers, and defines each layer using generic geometrical primitives, such as boundary/polygons, path/poly-lines, texts, boxes, structure references (SREF), and structure array references (AREF).

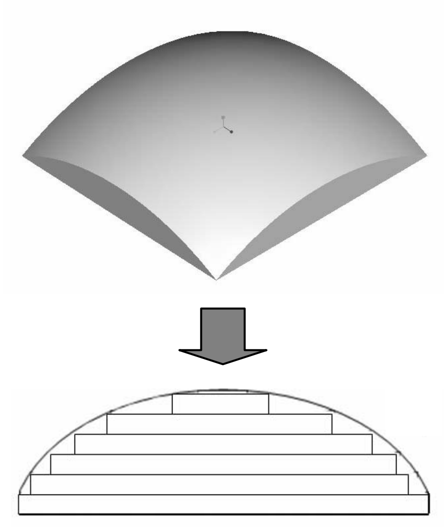

Fig. 2 The 3D CAD model created with ProEngineer and a schematic representation of the sliced model in N layers.

2.5. Setting-up of Process Parameters

The GDSII stream that represents 3D models as a stack of "N" layers can be used to fabricate 3D micro- and nano- structures by employing one of the available lithography tools, and thus to process the data in a layer-by-layer fashion. Hence, the number of layers and the dose factors assigned to them will affect directly the accuracy of the structures in the "build" direction. The lateral resolution is determined by the intrinsic properties of the particular source, column and deflection system setup, i.e. beam current, spot size and beam step size. For the practical implementation of this manufacturing strategy, it is required to set-up the FIB processing parameters such as ion current, dwell time, beam step size, number of loops, and the scanning strategy.

2.6. FIB data processing

GDSII files cannot be used directly by the available FIB systems. The data, however, can be used to control the FIB process by employing a pattern generator, a digital-to-analogue converter (DAC), which is an integral part of any lithography system. Thus, the role of this lithography system in the proposed approach is to control digitally the exposure strategies and parameters, for example the dwelling time, beam step size, dose factor, number of loops and scanning strategies. Furthermore, it can be used to modify the geometrical profile of each individual layer, and if required to select a single layer, a group of layers or all layers for processing and alignment using manual or automatic marks. In order to validate the proposed approach, in this study, the Raith lithography hardware and software, Elphy Quantum, has been employed.

The key advantage of the proposed CAD/CAM approach is the possibility to design the 3D micro- and nano- structures with various CAD packages, where complex 3D features can be created relatively easy. Moreover, by applying a set of software tools, the geometrical and processing data are generated and stored in a GDSII file that can be used for FIB processing, employing the available lithography tools.

3. Experimental setup

In order to validate the proposed CAD/CAM approach for fabricating 3D micro- and nano- structures, a series of experiments was conducted. The main objective of these experiments was to demonstrate that 3D structures can be produced from 3D CAD data employing layer-by-layer FIB processing.

A 3D model representing a square lens with dimensions 2.2 x 2.2 x 0.57 µm was selected for carrying out the experimental validation of the proposed approach. The 3D model, shown in Figure 2, was created employing ProEngineer, a 3D CAD package. Then, a STL file was generated utilizing the build-in translator for data export in ProEngineer. Finally, before proceeding to the slicing stage, the two STL files were validated employing the Magics RP software. This is an important step that allows the models to be checked for the existence of any "bad" edges and contours, and missing triangles. If there are errors, the model can be repaired in most cases automatically.

The Artwork Conversion software was used to slice the STL models and convert the data into a GDSII stream. For testing of the GDSII file, a Carl Zeiss XB1540 dual beam FIB/SEM system has been used that incorporates a Canion 31 ion column, a Gemini electron column and a gas injection system (GIS) with five precursor gases for gas assisted deposition or etching. The Elphy Quantum lithography hardware and software was employed to process the GDSII files for performing either sputtering using Ga ions or FIB-CVD using platinum gaseous precursors. The processing parameters for producing 3 x 3 arrays of concave or convex lenses were set up manually by the FIB operator.

All measurements were performed on the same dual beam FIB/SEM system utilizing the SmartSEM software.

4 Experimental validation

Arrays of concave and convex square lenses were successfully fabricated through FIB sputtering and platinum deposition, respectively, as shown in Figure 3. In Figure 3(a), the pattern was milled into Si(100) using a 30keV Ga^+ ion beam at 10 pA with an approximate spot size of 50 nm, full width at half-maximum. For deposition, as shown in Figure 3(b), a 30keV Ga^+ ion beam with a probe current of 2 pA was used. The gaseous precursor employed for FIB-CVD was *Platinum*, which caused the chamber pressure to rise to $2.0x10^{-5}$ mbar during exposure.

The exposure time for each experiment was approximately 15 minutes, allowing for a 3x3 array of lenses to be milled into or deposited onto the Silicon substrate. For both experiments, the same GDSII file, created with the proposed CAD/CAM approach, was utilized. The cross-sectional profiles of the convex and concave lenses produced in this way are given also in Figure 3. Analysis of these profiles confirmed that both structures had a shape very close to that in the CAD model. For the milling experiment, the deviation from the lateral dimensions is almost negligible; in particular, the target size of the lenses was 2.2 µm compared to 2.25 and 2.206 µm for the milled and deposited ones, respectively. However, for the selected processing parameters the deviations in the "z" direction was much higher, i.e. 37% and 51%, respectively. It can easily be seen in Figure 3 a) and b) that in both cases smooth curvatures were produced. For these particular tests, it is more interesting to know what the deviation from the target lenses' radius is. The measurements show that the radii are twice and three times bigger than the target values for milling and deposition, respectively. Regarding FIB-CVD, the deviation in the direction perpendicular to the lens plane is significantly higher due to factors not associated with the proposed data preparation technique such as: the use of non-optimized ion probe current, the relatively large steps employed in building the structure, non-uniformity of the precursor gas flux and sensitivity to variations in the vacuum conditions of the system. By optimizing the process parameters it should be possible to achieve the required geometrical accuracy.

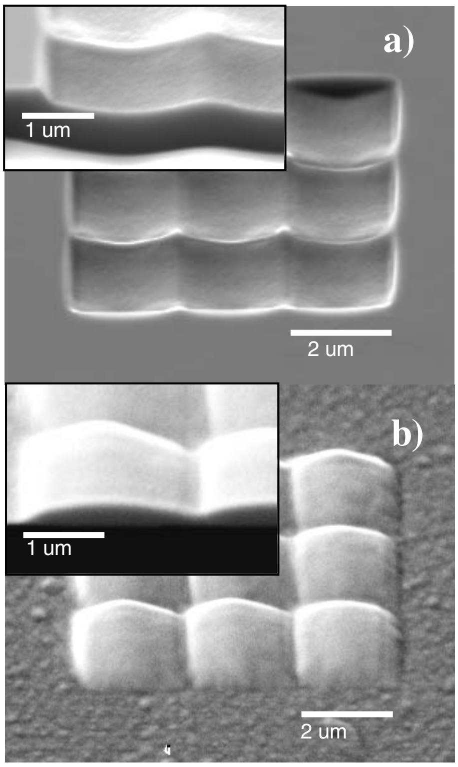

Fig. 3. SEM images at 36^{o} of 3x3 arrays of square lenses produced employing layer-based FIB processing: a) sputtering and b) Pt gaseous precursor assisted GA deposition.

Note: The inserts show SEM cross-sectional images of the lenses.

5. Conclusions

A novel and efficient data preparation approach is proposed in this paper for layer-based FIB processing of complex 3D micro- and nano- structures utilizing directly 3D CAD data. By applying this approach, complex surfaces can be designed easily in any 3D CAD package and then converted into GDSII streams for FIB machining.

The experimental validation conducted in this study demonstrated that, using this approach, 3D structures can be produced through either FIB milling or FIB-CVD. The test results showed that the deviation from the lateral dimensions was almost negligible. However, for the selected processing parameters the deviations in the "z" direction were much higher. This can be attributed only to the FIB milling or deposition parameters used in the trials because the uncertainties introduced by tessellating 3D CAD models, and then converting the generated STL files into GDSII streams are three orders of magnitude smaller than the experimentally observed errors. By optimizing these processing parameters it should be possible to achieve the required geometrical accuracy.

Finally, it is worth stressing that the proposed approach for data preparation opens new exiting opportunities for development of hybrid processing chains that combine the capabilities of FIB and e-beam pattering, and emerging multi beam systems, e.g. PMLP (Projection Mask-Less nano-Patterning), with those of ultra-short pulsed laser systems. By employing such hybrid processing chains it will be possible to achieve length scale integration in performing 3D structuring, and also expand the "windows" for cost-effective processing of these complementary technologies.

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