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Data preparation for focused ion beam machining of complex three-dimensional structures

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Abstract: The realization of complex three-dimensional structures at micro- and nanometre 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 three-dimensional 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 three-dimensional computer-aided design (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, lithography, three-dimensional nano- and microstructuring, FIB-CVD

1 INTRODUCTION

The realization of complex three-dimensional (3D) structures at micro- and nanometre scale in various materials is of great importance for a number of micromechanical, microoptical, and microelectronic applications. Especially, this is of importance for achieving functional integration in new and emerging products, such as biosensors, organic micro/nanophotonic 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 nanoimprint 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 nanostructuring of almost any material. 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 nanostructuring 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 maskless nano-patterning (PMLP) system is currently under development within a European FP6 integrated project 'Charged Particle Nanotech' (CHARPAN,

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Corresponding author: Manufacturing Engineering Centre, Cardiff University, Queen's Building, The Parade, Newport Road, Cardiff CF24 3AA, UK. email: lalevgm@cf.ac.uk www.charpan.com). 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 ×200 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 multibeam system together with the data preparation technique proposed in this paper, it will be possible to produce complex 3D surface structures with nanometre precision relatively fast, and at much lower costs than would be possible utilizing other lithography techniques [**11**].

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 (computer aided design/manufacture tools should satisfy the stringent requirements towards the geometric and dimensional accuracy of such 3D structures imposed by various applications, e.g. the fabrication of arrays of diffractive and refractive optical elements [**12**]. Another important requirement is that these tools should be compatible with data formats such as GDSII and Gerber, which are widely utilized by the 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 nanostructures. 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 nanostructures 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, but 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 Fig. 1. In particular, it includes the following steps.

1. *Three-dimensional data creation*. A CAD package, e.g. SolidWorks or ProEngineer, can be employed to create three-dimensional, unique, and complete representations of micro- and nanostructures. 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 [**13**]. Formally, such a model is valid if the system can determine uniquely for each point in the 3D space whether it lies inside, on, or outside the object surfaces. Such models allow the same data to be used in different engineering tasks from documentation (drafting), to engineering analysis, rapid prototyping (RP), and manufacturing.
2. *Data export*. The valid 3D model has to be exported from the CAD package into a suitable format for CAM downstream applications. There are two main methods for data exchange in CAD/CAM systems, i.e. employing direct or indirect translators. In the first case individual translators are required to exchange data between each CAD/CAM combination. This provides a satisfactory solution when only a small number of systems is involved, but as this number increases the number of translator programs that have to be written becomes prohibitive. Conversely, in the second case, the data can be exported in a neutral database structure and thus translators are needed only between each CAD or CAM system and the selected neutral format. As a result the number of required translators will be significantly less than when employing direct translators. For example, if n CAD systems and m CAM systems are considered, the direct method will require $(n \times m)$ translators, while for the indirect method $(n+m)$ translators will be sufficient for one-way data transfers between CAD and CAM systems. Therefore, the indirect method is adopted in the proposed CAD/CAM approach. Hence, the choice of a neutral file format becomes a critical issue since the exported data should contain not only 3D information about the model but also be transferable to different CAD and

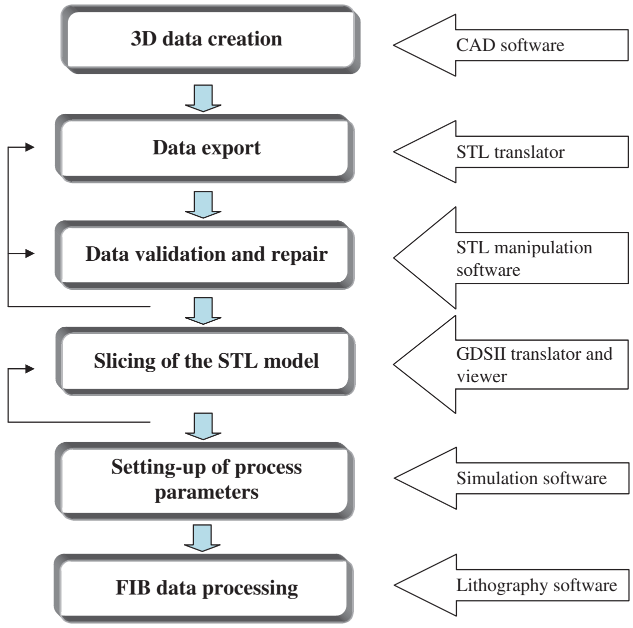


Fig. 1 The key steps of the proposed CAD/CAM method for layer-based FIB processing

CAM systems, and their different versions without losing information. Taking this into account, the stereolithography (STL) neutral file format [**14**] 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 modelling 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.

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 [**13**]. 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 the case of errors, the gaps in the models are filled with new triangles. In the CAD/CAM approach proposed here, Magics RP [**15**], an STL manipulation software, is employed for data validation and, if required, for repair of the STL model.
4. *Slicing of the STL model*. The 3D model in STL format has to be sliced in order to produce successive cross-sectional layers. 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. [**16**] 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).
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 nanostructures 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 set-up, i.e. beam current, spot size, and beam step size. It is, however, also possible to adopt a different FIB processing strategy for producing the structures; firstly, to convert the sliced data in the GDSII stream into a 'grey' tone format, a bitmap format, and then to fabricate them by varying the exposure time assigned to each pixel. These two different strategies are shown graphically in Fig. 2. For their practical implementation, 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. This can be

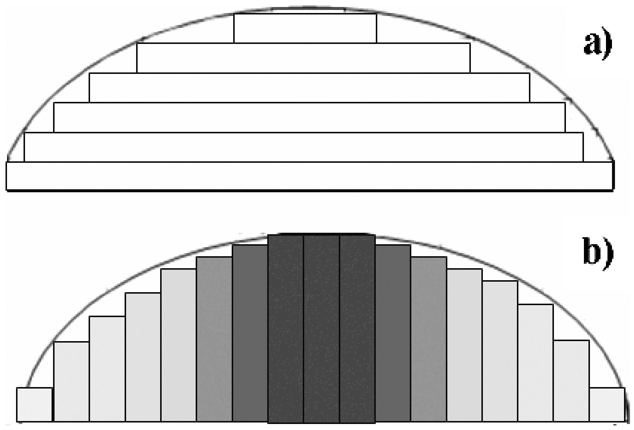


Fig. 2 Processing strategies: (a) slicing into *N* layers and (b) converting into a 'grey' tone

done manually or automatically employing simulation software that takes into account the effects of different process-specific factors on geometrical and dimensional accuracy of the fabricated features. For example, the re-deposition of sputtered material, the occurrence of over-etching, the selected scanning strategy, the ion current, and the dwelling time employed, all affect the accuracy of the produced structures. To minimize their negative effects it is possible to optimize the processing parameters and/or modify the model. For example, the recently developed software, IonShaper^{TM} [**11**], can be employed to optimize these parameters. In this study only the layer-by-layer processing strategy is applied to demonstrate the feasibility of the proposed CAD/CAM approach and the setting-up of the processing parameters was carried out manually by the FIB operator.

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 [**17**]. In particular, it transmits directly to the FIB system the coordinates of the points that define the geometrical profile of each layer. All of the internal points for exposure are generated through the patterning hardware that controls the FIB deflection system by varying the voltage applied to the column coils. This is done on-line by lithography hardware and software that takes over the control of the layer-by-layer FIB sputtering or deposition. Thus, the role of this lithography system in the proposed approach is to control digitally the exposure strategies and parameters, e.g. 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.

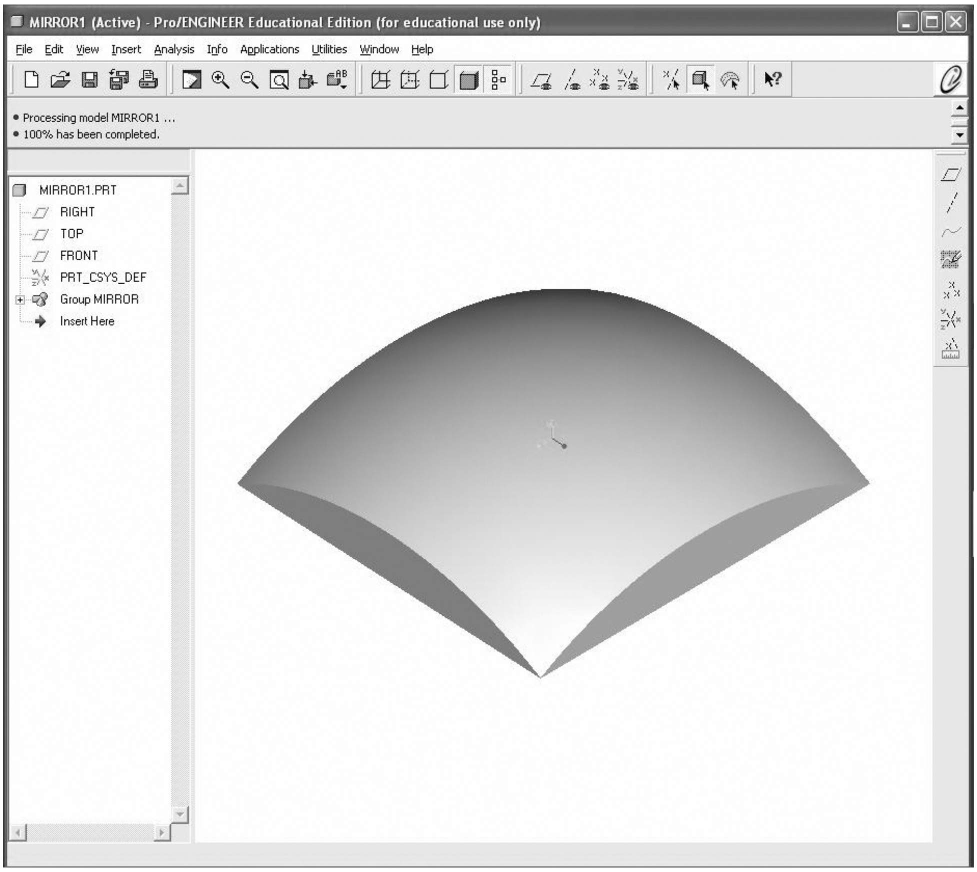
The key advantage of the proposed CAD/CAM approach is the possibility to design the 3D micro- and nanostructures with various CAD packages, where complex 3D features can be created relatively easy. Moreover, by applying a set of software tools, the geometrical and processing data are generated and stored in a GDSII file that can be used for FIB processing, employing the available lithography tools. However, by adopting this layer-by-layer manufacturing approach the accuracy of the structures produced by FIB sputtering or deposition could be affected by different factors that introduce errors due to the carried-out tessellation and then slicing of the 3D models, in combination with other specific processing problems. These effects are briefly described in the discussion section of this paper.

3 EXPERIMENTAL SET-UP

In order to validate the proposed CAD/CAM approach for fabricating 3D micro- and nanostructures, 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 μm × 2.2 μm × 0.57 μm was selected for carrying out the experimental validation of the proposed approach. The 3D model, shown in Fig. 3, was created employing ProEngineer, a 3D CAD package. Then, an STL file was generated utilizing the build-in translator for data export in ProEngineer. In particular, two STL model files with a different resolution were created. The resolution of the models was controlled by varying the tessellation parameters [**18**]. In the present case, different chord heights were applied to approximate the lens surface with 3480 and 1020 triangles respectively, as shown in Figs 4(a) and (b). This was done in order to assess the effects of the model resolution on the accuracy of the GDSII files generated from them. 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



• Processing model MIRROR1 ...
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Fig. 3 The 3D CAD model created with ProEngineer

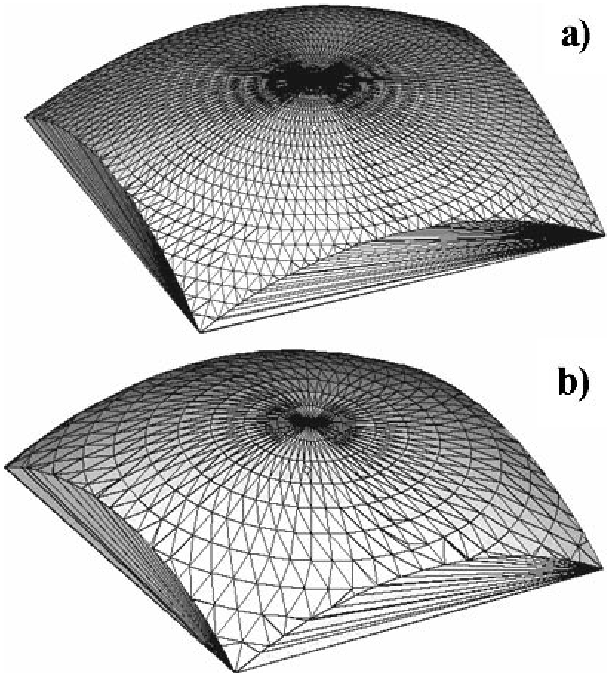

Fig. 4 The STL models generated with two different tessellation parameters: (a) a lens representation with 3480 triangles and (b) a lens representation with 1020 triangles

stream. For layer-by-layer FIB processing, GDSII files containing 52 layers were generated. Although the maximum number of layers supported by this slicing software is 1025, the Elphy Quantum lithography system can be used to process GDSII files containing only up to 64 layers including those for automatic and manual alignment marks. To verify whether the GDSII files generated employing this CAD/CAM approach are readable by other lithography tools as well, the data have been loaded into CATS, a software package developed by Transcription Enterprises Inc., which is widely used for converting GDSII data into a machine-readable format for electron beam lithography.

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 were 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 3×3 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 Fig. 5. In Fig. 5(a), the pattern was milled into Si(100) using a 30 keV Ga^+ ion beam at 10 pA with an approximate spot size of 50 nm, full width at half-maximum. For deposition, as shown in Fig. 5(b), a 30 keV Ga^+ ion beam with a probe current of 2 pA was used. The gaseous precursor employed for FIB-CVD was platinum (C9H16Pt), which caused the chamber pressure to rise to 2.0×10^{-5} mbar during exposure.

The exposure time for each experiment was approximately 15 min, allowing for a 3×3 array of lenses to be milled into or deposited on to 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 Fig. 5. 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 per cent respectively. It can easily be seen in Figs 5(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 lens radius is. The measurements show that the radii of milled and deposited lenses are bigger than the target one (2.4 μm radius), with 20.8 and 64 per cent, 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. Preliminary experiments show that by varying the dwell time, step size, and number of loops the target depth and radius can be easily achieved. The effect of these parameters on the geometrical accuracy will be discussed in detail in a separate publication.

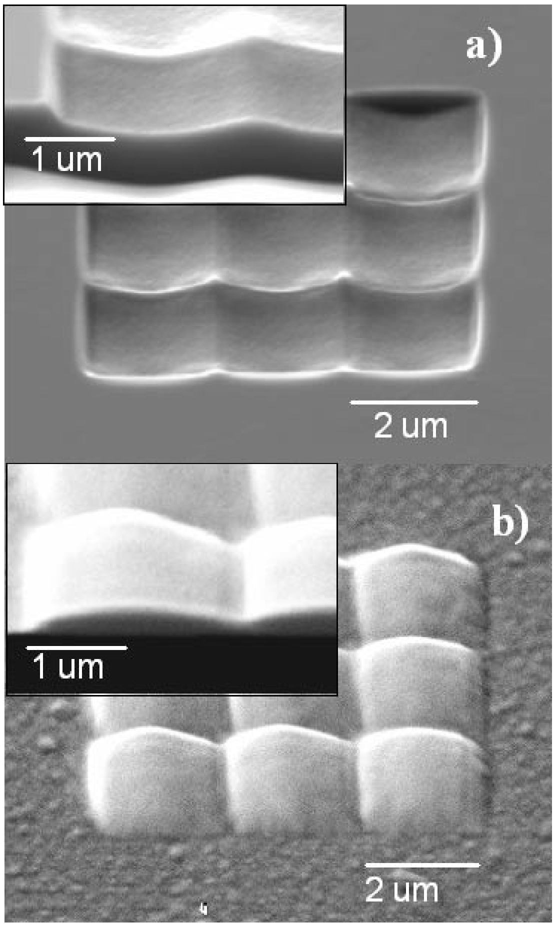

Fig. 5 SEM images at 36° of 3×3 arrays of square lenses produced employing layer-based FIB processing: (a) sputtering and (b) Pt gaseous precursor assisted deposition. Note that the inserts show SEM cross-sectional images of the lenses

5 DISCUSSION

The experimental study conducted here demonstrates the feasibility of the proposed approach for producing 3D structures from 3D CAD data applying layer-based FIB processing. Also, this study revealed different factors affecting the accuracy of the fabricated structures. However, to develop this approach further, it is required to study the uncertainties that each of these factors introduces, and thus minimize their effects. Especially, this is necessary in order to satisfy the stringent requirements towards the geometrical and dimensional accuracy of 3D micro- and nanostructures imposed by various applications. Therefore, in this section, an attempt is made to outline the main sources of errors that affect the accuracy of structures produced by layer-based FIB processing. Also, they are indicative of the errors that will be present if the proposed CAD/CAM approach is applied to PMLP [**10**].

5.1 Errors due to surface faceting

Since the faceting of the surfaces in 3D models introduces errors in STL files [**19**, **20**], the number and the size of the triangles determine how accurately the surface mesh represents the model. The resolution of STL files can be controlled during their generation in 3D CAD systems by setting up tessellation parameters. For example, in ProEngineer, the STL generation process can be controlled by specifying the chord height or the angle control factor [**18**]. Other factors influencing the STL accuracy are mistakes due to missing facets, non-manifold facets, overlapping facets, and incorrect normals.

The effects of the size and the number of triangles on the geometrical accuracy of a 3D structure can be illustrated with two STL models representing the same square lens with dimensions 2.2 μm × 2.2 μm × 0.57 μm, but approximated with 3480 and 1020 triangles as shown in Figs 4(a) and (b) respectively. The errors introduced by the faceted surfaces of the two models, i.e. the deviation from the actual design, are schematically given in Fig. 6. The calculated maximum errors were 0.044 and 0.16 nm for the models with 3480 and 1020 triangles respectively. The effect of tessellating the 3D design can be seen in GDSII files only after slicing. The GDSII file created from the STL file with 1020 triangles consists of layers with clearly defined facets, as shown in Fig. 7(b).

It can clearly be seen that the facets are much better defined in the GDSII file generated from the STL model where the surfaces are approximated with a larger number of smaller triangles. It is also worth mentioning that, in this particular case, in contrast to the original STL files, the size of GDSII files does not depend on the number of triangles used to tessellate the 3D model, but is influenced only by the number of layers. The effect of the number of triangles on the size of the STL files, their accuracy, and the size of their corresponding GDSII files as a function of the number of layers is given in Table 1 for an array of 10 × 10 lenses. Note that the file size per layer is independent of the STL file resolution; this is due to the fact that circles in GDSII are represented by polygons with 256 coordinate points by default, whereas in the examples given in Figs 3, 4, and 7 and in Table 1, 3480 and 1020 triangles were approximated employing 128 and 64 coordinate points per circle respectively. Hence, the higher resolution available for the GDSII circles was not utilized, but additional interpolation points were generated on the polygons instead of on the circle periphery (see Fig. 7).

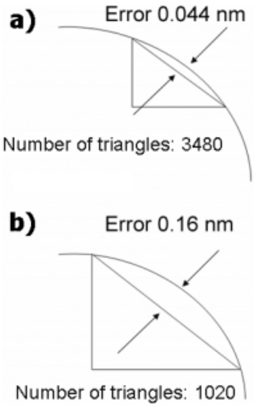

Fig. 6 A schematic representation of the error due to the representation of the lenses with faceted models: (a) a model approximation with 3480 triangles and (b) a model approximation with 1020 triangles

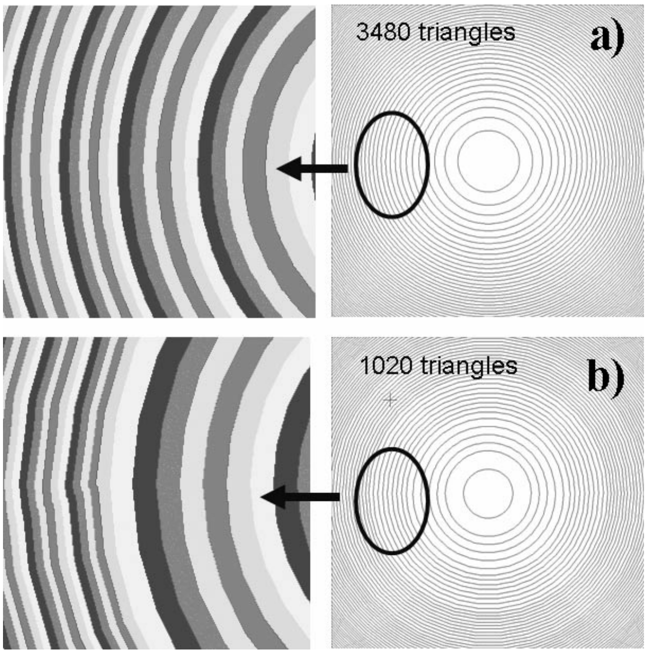

Fig. 7 The faceting effect on the GDSII layer resolution after slicing the STL models: (a) a model approximation with 3480 triangles and (b) a model approximation with 1020 triangles

Table 1 The effects of the model resolution on the STL file and the GDSII stream for an array of 10 × 10 lenses

STL data (10 × 10 arrays square lenses)				GDSII stream	
		File size		File size (from STL in binary format)	
Number of triangles	Error (nm)	Binary	ASCII	63 layers	569 layers
348 000	0.044	17 100 kB	63 000 kB	2400 kB*	22 800 kB*
102 000	0.16	5000 kB	16 840 kB	2400 kB*	22 800 kB**

*Note that the file size per layer is independent of the STL file resolution.

Thus, it can be concluded that when applying the CAD/CAM approach proposed here, it is beneficial to set up one of the tessellation parameters, the chord height, or the angle control factor as high as possible when exporting 3D data in STL format in order to approximate the 3D surfaces with a maximum number of triangles. At the same time, the number of layers used to represent a 3D STL model when creating a GDSII stream should be determined individually for each model depending on its complexity and the required resolution of the structures produced by layer-based FIB processing. In some cases, working with too many layers is impractical owing to the consequent increase of the file size and also additional constraints introduced by some lithography systems, e.g. by the Elphy Quantum system, which cannot handle more than 64 layers.

5.2 Errors due to 3D model slicing

The stair-stepping effect is a common problem for all layer-based manufacturing technologies. Stair-stepping is a consequence of the removal or addition of material in discrete layers. As a result of this layering, the shape of the original CAD models in the processing direction, usually *Z*, is approximated with stair-steps. In general, there are two types of error resulting from the slicing opertation; one is due to mismatching in height between slice positions and feature boundaries while the other is due to the replacement of polygons with stair-steps.

The stair-steps particularly affect slight slopes. This problem mainly influences the surface quality of products and can be alleviated by reducing the thickness of the layers. The layer thickness, however, cannot be indefinitely decreased, and a compromise has to be found between the thickness of the slices and the processing speed. This problem can be partially overcome using adaptive slicing that generates slices with different thicknesses as a function of the local curvature of the 3D model [**21**]. Also, it would be useless to reduce the layer thickness below the vertical resolution limit of the lithography tool employed. The ultimate limit is anyway reached in nanopatterning applications, when the layer thickness gets closer to the dimensions of the atoms. In this case the stair-steps in the sliced model are of the same order of magnitude as the atomic or molecular lattices to be structured, which can lead to further deviations, e.g. due to Moire fringes. However, it is worth noting that currently the resolution limit of the FIB systems is at least one order of magnitude above atomic and molecular dimensions.

5.3 Processing errors

Different process-specific errors affect the final accuracy for the produced 3D micro- and nanostructures. For example, the re-depositioning of the sputtered material, the occurrence of over-etching, the selected process parameters such as ion current and dwelling time, and errors due to the selected scanning strategy are significant factors influencing the product accuracy. All these effects can be reduced by optimizing the FIB process and/or modifying the model.

In addition, in order to improve the surface quality of the products, finishing steps could be introduced. In particular, typical techniques for surface improvements are beam defocusing, flushing with etching gas precursor, or final milling with a very low ion current. The model accuracy after the finishing operations is influenced mostly by two factors, the varying amount of material that is removed and the specific characteristics of the employed finishing technique.

5.4 Data manipulation and translation

There are two different ways of performing FIB processing utilizing the data created by the proposed CAD/CAM approach. As already mentioned, it is possible to mill or deposit material by performing layer-based processing, using the sliced data stored in the GDSII stream or converting these data into a 'grey' tone, as shown schematically in Figs 2(a) and (b) respectively. Slicing into *N* layers is a common approach for layer-based manufacturing, where the 3D geometry is defined by the shape of the slices and the steps between them. The dose factor could be the same or different for each layer, in contrast to the grey tone model, where different exposure values are required for each pixel in order to obtain the desired 3D shape. Slicing into *N* layers is a universal way of producing any 3D shape. There are, however, some restrictions concerning the shape of the model, when using a grey tone approach; e.g. undercuts cannot be realized.

The software employed to slice the STL models can also affect the accuracy of 3D micro- and nanostructures produced by layer-based FIB processing. In particular, the selected software has to support the generation of cross-sectional profiles with optimum resolution, and also to offer capabilities for specifying very small steps between the layers. This is specially required when the critical dimensions of the model are in the submicrometre range. In the proposed CAD/CAM approach, the Artwork Conversion software is employed to carry out the slicing of the STL model. Based on the feasibility study conducted here, it is difficult to judge the effects of this software on the accuracy of the structures produced by layer-based FIB processing in general. Further research is required in order to assess the uncertainty that this software adds to the data preparation process.

It is also important to verify whether the GDSII files generated by this CAD/CAM approach are readable

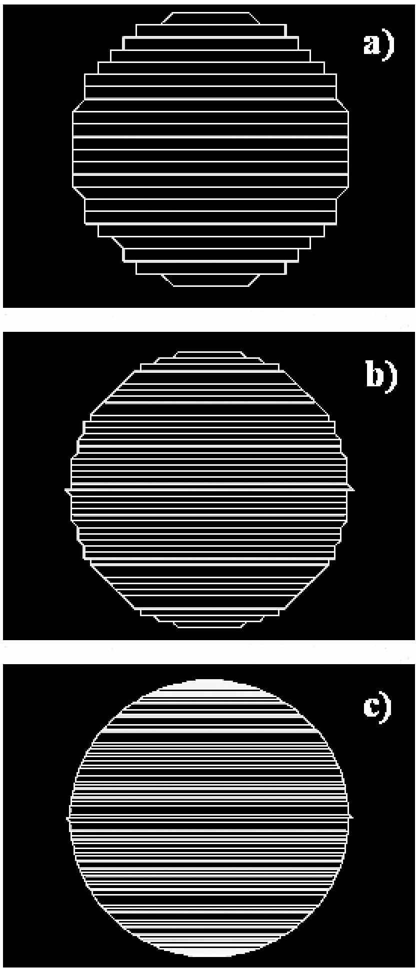

Fig. 8 CATS screen shots of the top GDSII layer (number 52) segmented in trapezoids for e-beam patterning with a resolution of: (a) 10 nm, (b) 5 nm and (c) 1 nm

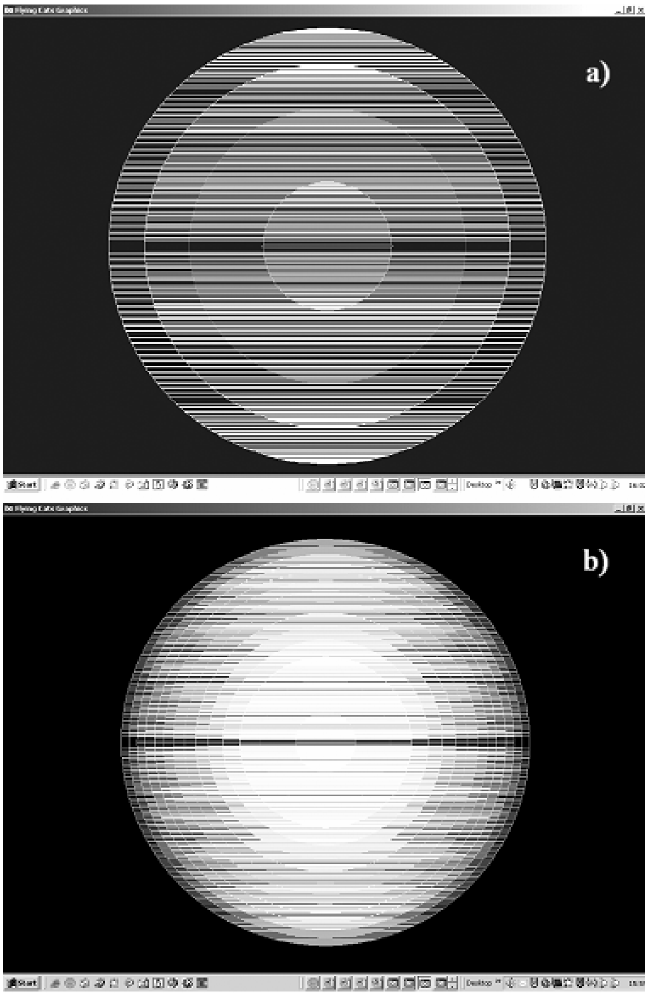

Fig. 9 CATS screen shots of the lens GDSII model prepared for e-beam patterning with a resolution of 1 nm: (a) layers 49 to 52 and (b) layers 39 to 52

by other lithography tools. The following test was conducted to demonstrate the compatibility of these files with the CATS software package, which converts the GDSII stream into machine readable format for electron beam pattern generators. In Fig. 8, the top layer of the GDSII data-set for one of the lenses (see Figs 3, 4, and 7) is shown as segmented by CATS for electron beam patterning with a resolution of 10, 5, and 1 nm. Note that CATS converts data in trapezoids to be written by the e-beam lithography tool. The screen shots show clearly that at a higher resolution the circles were converted in a more reliable way, as anticipated. In Fig. 8(c), the only observable deviations are sharp edges at the periphery of the circle on both sides of the central horizontal diameter line ($y = 0$), but these features are only 1 nm in size. In Fig. 9, several stacked layers of the same lens structure are shown. For practical visualization purposes, the number of displayed layers has been limited. It can be concluded that the stacked GDSII layers, as generated by the CAD/CAM approach proposed here, are readable by other lithography tools and their resolution is satisfactory.

6 CONCLUSIONS

A novel and efficient data preparation approach is proposed in this paper for layer-based FIB processing of complex 3D micro- and nanostructures 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 patterning, and emerging multibeam 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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