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Process chain for serial manufacture of 3D micro- and nano-scale structures

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ABSTRACT

This paper presents a cost effective route for serial fabrication of 3D structures and the achievement of function and length scale integration (FLSI) in products. A complex 3D functional pattern was designed and then used to validate this route for serial manufacture of component that integrates micro and nano scale functional features. It employs a viable master-making process chain that integrates, innovatively compatible and at the same time complementary, structuring and replication technologies to fabricate Ni shims. The shims are then utilised for the hot embossing of structures incorporating different 2.5D and 3D length-scale features. The resulting 3D profiles at different stages of the process chain were investigated and the factors affecting its overall performance were analysed.

1. Introduction

In recent years the trend towards product miniaturisation, together with advantages that the integration of multiple functions into a single component could bring, "fuelled" the interest in developing manufacturing solutions for producing features/structures with dimensions ranging from millimetre to nanometre scales onto a single product. In this paper it is referred to as a trend towards and/or respective manufacturing routes for achieving Function and Length Scale Integration (FLSI) in products.

FLSI is a product development approach that offers many advantages such as reduction of production cost and time, as well as products' overall dimensions (Bigot et al., 2009). The methods for achieving FLSI can be classified into three main types: assembly, single process machining/structuring and multi-process fabrication of a single component. Although a broad range of technologies can be utilised in micro and nano manufacturing they are viable only in their cost effective processing window in regard to features' sizes and/or throughput. Therefore, to achieve FLSI in products it is necessary to look for or develop process chains that combine the capabilities of complementary technologies (Bigot et al., 2009; Brousseau et al., 2009; Allen et al., 2008). Such multi-process fabrication paradigm for a single component relies on novel integrations of manufacturing technologies, which operate in their cost-effective processing windows, to design and implement viable manufacturing platforms (Velkova et al., 2010; Scholz et al., 2009). The aim of such technology integration is to multiply innovatively the capabilities of component technologies, and in this way the advantages of compatible and at the same time complementary processes are utilised at their best while reducing the impact of their shortcomings on the overall product realisation.

In many application areas like optics, optoelectronics and biomedical industry, the realisation of complex multiple three dimensional (3D) structures at micro and nano scales is a crucial issue that poses further constraints in designing and implementing successful FLSI manufacturing solutions. Such applications usually require structures like lenses and pyramids, having micron and/or nanometre dimensions, to be produced as large arrays rather than as single features i.e. structured surfaces containing numerous 3D features (Lee et al., 2006; Päivänranta et al., 2008; Yan et al., 2009). Usually, there are strict technical requirements in regard to such arrays of 3D features, e.g. geometrical accuracy, aspect ratio (AR), positional and alignment accuracy and field stitching, which make the design and implementation of cost effective solutions for their manufacture even more difficult. A major issue in manufacturing 3D structures at different scales in order to achieve FLSI arises from the high uncertainties associated with the achievable dimensional accuracy of the resulting profiles, especially in vertical direction (Lalev et al., 2008). Therefore, it is important to study the various factors affecting the 3D structuring process chains starting from their designs and then going through their implementation stages.

The design and validation of a manufacturing route for fabricating templates for Nano Imprint Lithography (NIL) that incorporates micro and sub-micron/nano 3D features on a millimetre scale mesa was reported in another study (Lalev et al., 2009). In this paper the successfully imprinted, with such templates, wafers were utilised as masters for the production of Ni shims. In particular, by adapting an already validated process chain for fabricating replication masters (Velkova et al., 2010), shims containing 3D micro and nano structures were produced and then employed for serial replication through hot embossing.

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2. Process chain design issues

2.1. Selection of 3D functional structures

As it was already mentioned arrays of pyramids are commonly utilised as functional features in various application areas. The micro pyramids, as structures incorporated into larger-scale products find important applications in the field of electronics, e.g. light emitting diodes and liquid crystal displays (LCDs) (Chen and Chien, 2006) and optical systems (Coquillat et al., 2008). They can also be utilised in micro-fluidic devices where pyramid structures located on the bottom of a 200 μm channel could facilitate and speed up liquids' mixing or act as traps for microbeads (Toepke and Kenis, 2005). Other application areas are micro-optical devices and MOEMS where arrays of pyramids are used to manipulate light in order certain improvements in the devices' properties to be achieved. That is due to their geometry that allows multiple refraction and reflection of light, having the pyramids' sides act like mirrors. Therefore it is important that the sides have very good surface roughness in the range from 3 to 5 nm (rms) (Trupke et al., 2006; Lin et al., 1998).

Arrays of micro pyramids are also used to increase the light extraction efficiency (LEE) of light emitting diodes (LEDs) (Lee et al., 2007) as well as to enhance the brightness of LCDs (Lee et al., 2006; Lin et al., 2000). Especially, the pyramids in these applications are employed to manipulate light emitted at them in three different modes: direct and indirect recycle and effective refraction. For example, if placed on the top of polymer films, pyramids' sides refract and reflect light so that it propagates through several of them. As a result redirecting and redistribution of light occurs thus increasing its intensity in the viewing angles ±35°.

2.2. Pattern generation

The patterning flexibility and sub-50 nm resolution that the Focused Ion Beam (FIB) technology offers for 3D structuring are utilised in this study (Youn et al., 2006). Two main data preparation approaches can be applied for FIB milling of 3D patterns: the use of bitmap data files by software built-in in the FIB systems or GDSII data files with the FIB milling process being externally controlled by conventional lithography software (Lalev et al., 2008).

In the first case each bitmap data file represents a cross-section of the 3D structure, i.e. it can be regarded as one slice from a stack of slices defining a given 3D shape. Therefore, a sequence of such cross-sections or a stack of bitmap files is necessary to produce a 3D feature/structure. As they are processed one by one with the built-in FIB software while the probe current and milling time for every single file has to be specified manually, this is a very slow and impractical approach. In addition, the precise alignment of the layers cannot be guaranteed and also errors in the layers' exposure order are possible. Thus, this approach can compromise the accuracy of the targeted 3D structure.

In contrast, the second approach allows for creating and exposing of the whole 3D model as a single file. Standard CAD packages are used to create the 3D models of the targeted structures and then they are exported into neutral data files using stereolithography (STL) format. This file format is used due to its acceptance as an industry standard data exchange format for layer-based manufacturing and its simplicity. However, the STL files cannot be applied for FIB milling directly, and therefore they have to be converted into the GDSII stream file format. It can be utilised to mill the 3D features directly, while the FIB is externally controlled by lithography software. The GDSII files can be utilised to realise two different FIB machining modes, in particular layer-based and quasi-stationary modes presented schematically in Fig. 1.

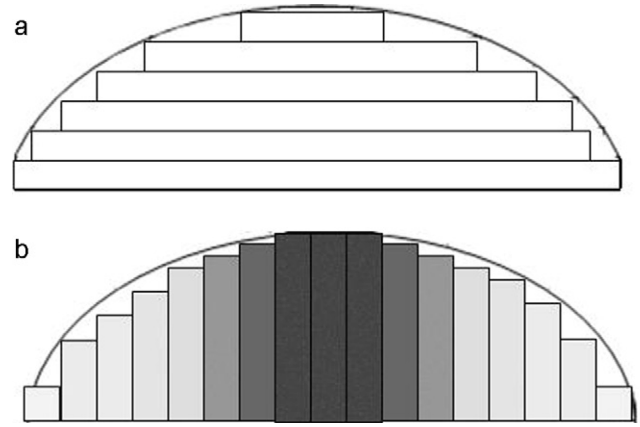

Fig. 1. FIB machining modes: (a) layer-based and (b) quasi-stationary.

In the first mode the 3D geometry is defined as a stack of layers ordered along the vertical axis of the feature or structure (Fig. 1a). Each layer represents a cross-section of the 3D model at a given height along its *z*-axis. The number of layers determines the accuracy of the feature/stricture that will be produced. In general, a bigger number of layers will result in a better resolution and profile accuracy. However, there might be some constraints regarding the number of layers that can be used to represent a given 3D model due to some limitations of the lithography software. All the layers are machined in a strict bottom-to-top sequence.

In the second mode the overall exposure dose for a given 3D structure is divided into a number of smaller doses. Each of them is assigned to an exposure pixel of the model. The dose at each pixel is determined by the targeted structure depth at the respective point. This could roughly be viewed as a vertical slicing of the model, as shown in Fig. 1b.

To facilitate the file generation and also to minimise the number of translations between software formats new software for data preparation and generation, IonRevSim, was developed specially for FIB machining (Svintsov et al., 2009). One of its advantages is that, when utilised in its layer-based mode, there is no upper limit to the number of layers that can be used to define a structure and the maximum number is determined by the minimum layer thickness. Furthermore, when the GDSII file is transferred to the lithography software all the pre-defined layers are embedded into one zero' layer and therefore the 'maximum 64 layers' restriction posed by the software can be eliminated.

Even though there are sputtering rate simulation softwares available to estimate the resulting layer depth after FIB machining and therefore the overall vertical size of the 3D geometry it is not a trivial task to set up the processing parameters so that the actual structure's depth matches the targeted one (Velkova et al., submitted for publication).

However, since the aim of the structuring stage of a process chain is to successfully produce arrays of high resolution 3D features, the pattern data preparation approach offering most advantages with regard to generation of complex 3D geometries was selected, i.e. the desired structures were created and input for FIB milling as GDSII data file.

2.3. Process chain

A validated process chain for fabricating replication tools was selected in this study to produce by hot embossing small series of structures containing 3D micro and nano features (Velkova et al., 2010). This master-making route employs compatible and complementary technologies for micro-structuring and sub-micron and nano patterning in order to fabricate Ni shims