Fabrication and diagnostics of micro/nanodevices by means of synchrotron radiation

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Abstract. SSLS’ technology basis in micro/nanofabrication encompasses the full LIGA process in a class 1000 cleanroom. This technology is used for an R&D programme and foundry-type work for commercial customers. R&D achievements include the development of the first electromagnetic metamaterials for the terahertz spectral range up to the near infrared. Complementing micro/nanofabrication, SSLS is exploiting its portfolio of synchrotron radiation methods for the characterisation of key properties of the micro/nanodevices as exemplified by the infrared spectroscopy of the THz electromagnetic metamaterials or diffractive optical elements for Fourier transform spectroscopy.

1. Introduction

A synchrotron radiation facility such as the Singapore Synchrotron Light Source (SSLS) is an ideal place for micro/nanofabrication including X-ray proximity lithography and EUV projection lithography. Furthermore, at a synchrotron light source, micro/nanofabrication can benefit from analytical beamlines for advanced device diagnostics such as refractive contrast X-ray imaging and tomography, infrared spectro/microscopy, and X-ray reflectometry.

SSLS has set up a complete one-stop shop for micro/nanofabrication in the framework of the LIGA process [1]. It is dubbed LiMiNT for Lithography for Micro and Nanotechnology. Fully operational since 2003 [2], its equipment allows prototyping using the integral cycle of the LIGA process for producing micro/nanostructures.

SSLS is exploiting refractive contrast X-ray imaging and tomography for the characterization of resist devices, infrared radiation for the spectroscopy of electromagnetic metamaterials (EM) in the THz spectral range and for the characterization of diffractive optical elements (DOE) in the near and mid infrared, as well as X-ray reflectometry for the characterization of surfaces and thin film multilayer systems in terms of their thickness, density, and roughness of surfaces and interfaces including even buried ones. It is also working at the in situ characterization of processes via X-ray absorption fine structure (XAFS) spectroscopy.

In this paper, we first outline SSLS’ technology basis, existing and projected, and the research and development programme. We then present results in the fields of EM in the THz spectral range and DOE in the near and mid-infrared. Finally, we give examples of the advanced device characterization with synchrotron radiation methods, and conclude with a remark on the comprehensive nature of the
use of synchrotron radiation when it comes to the fabrication and characterisation of micro/nanodevices.

2. Technology base

2.1. Existing technology portfolio
The currently available equipment allows complete prototyping using the integral cycle of the LIGA process for producing micro/nanostructures. It extends from mask writing via either laser direct writing or e-beam lithography over X-ray irradiation, development, to electroplating in Ni, Cu, or Au, and, finally, hot embossing in a wide variety of plastics as one of the capabilities to cover a wide range of application fields and to go into higher volume production. The process chain also includes plasma cleaning and sputtering as well as substrate preparation processes including metal buffer layers, plating bases, and sacrificial layers, as well as spin coating, polishing, and dicing. Furthermore, metrology using scanning electron microscopy (SEM), optical profilometry, and optical microscopy is available (fig. 1). Except for dicing and polishing, these processes are all located in a class 1000 cleanroom. Diagnostics using analytical beamlines is spread over the whole experimental floor of SSLS.

Fig. 1: Schematic layout of the LiMiNT facility for micro/nanofabrication at SSLS.

Fig. 2 shows a schematic layout of the whole SSLS facility regarding, in particular, the beamlines and experimental stations.

2.2. Planned extension of technology portfolio
SSLS and the Center for Ion Beam Applications (CIBA) at NUS have teamed up to study the direct fabrication of masks for deep X-ray lithography by means of proton beam writing using CIBA’s up to 3.5 MeV proton beam, eventually providing a unique tool for mask fabrication worldwide [3]. Expected advantages include a

- simplification of the process of producing X-ray masks as there would be no more need to write intermediate masks of 1 to 2 µm thickness of the Au absorber and to copy them with soft X-rays into resist layers that are thick enough to plate Au absorbers 10 µm thick or more as suitable for specific X-ray exposures, and an
enhanced smoothness of the absorber edges.

Furthermore, plans have been worked out for setting up a single-field exposure camera for Extreme Ultraviolet (EUV) nanolithography [4] that is dubbed ENALFA by now. Based on the copious amounts of EUV in-band radiation at 13.5 nm wavelength as provided from the Helios 2 storage ring and on the typically 4× demagnifying projection of a multilayer Schwarzschild objective, the ENALFA facility would be used to study the generation of device features as small as 10 nm and below. This order of achievable feature size would allow bridging the gap between nanostructure formation by self assembly and fabrication of fan-in fan-out structures by nanolithography such as to produce practically useful nanodevices that are related to the macroscopic world.

Fig. 2: Schematic layout of SSLS and its beamlines and experimental stations.

3. Research and development in micro/nanofabrication

SSLS’ work on micro/nanofabrication is structured along two major lines, namely, the research programme and the contractual work for customers in which latter case SSLS is acting like a foundry. In the following, these aspects will be described in more detail.

3.1. R&D fields

SSLS’ R&D fields include the development of micro/nanodevices and processes to fabricate them. Device development is focused on electromagnetic metamaterials (EM3) in the THz spectral range [5], near infrared photonics devices with applications in telecommunications, infrared diffractive optical elements for fast parallel-processing Fourier transform interferometry [6, 7], i.e., without moving parts, X-ray micro-optical mirror arrays, nanofilters, and nanosensors [8].

3.2. Achievements in device development

3.2.1. Device research. Two examples of device fabrication will be given, one concerning the development of electromagnetic metamaterials, another dealing with diffractive optical elements for the infrared.

SSLS has produced the first THz EM3 by microfabrication. The resonance frequency of those samples produced by microfabrication extended from 1.5 to 2.4 THz [5]. As discussed by Veselago as
early as 1967 [9], such EM$^3$ exhibit both, dielectric permittivity and magnetic permeability, simultaneously negative within a certain frequency bandpass. This entails panoply of unusual optical properties including a negative refractive index. Promising applications abound, a specifically interesting one being the sub diffraction limit imaging in the infrared that would allow infrared microscopy with enhanced resolution. Other potential applications are in the field of sensors [8] and optical components such as couplers. Meanwhile, SSLS has succeeded to extend the accessible spectral range by two more orders of magnitude by means of nanofabrication of such EM$^3$ to resonance frequencies approaching the near infrared spectral range as used in telecommunication [10]. Fig. 3 shows a resonance curve and a picture of such an EM$^3$ at 187 THz that is close to the 193 THz that correspond to 1.55 μm wavelength used in fibre optical telecommunication. Work towards 3D EM$^3$ that have more isotropic response to incident waves than the planar ones mostly produced so far is also underway [11].

SSLS is also working on infrared diffractive optical elements (DOE) [6, 7] that aim at setting up fast parallel-processing infrared Fourier transform interferometers. Intended applications include high-bandwidth non-periodic phenomena like explosions or combustion processes that are not readily amenable to standard Fourier transform interferometers that usually feature mechanically scanning mirrors.

Fig. 4 (inset) illustrates the principle of the diffractive optical element that is the heart of the system. A checkerboard-like area of $n^2$ single square fields is formed such that each field has a discrete different height. This checkerboard is then covered to 50% by high-aspect-ratio lamellae the top surface of which is at the same level such that there is an array of cells featuring different depths. Radiation impinging on that device will be split into a fraction reflected by the top of the lamellae and another fraction reflected at the bottom of the checkerboard. Different depths translate into different optical path lengths and interference phenomena. Each field is imaged on a specific field of an array detector the signal of which then constitutes an interferogramme which is evaluated in the usual way. Fig. 4 also includes simulated and measured interferograms of such a diffractive optical element. Fig. 5 shows an SEM picture of test lamellae.
3.2.2. Foundry work. SSLS is increasingly active for commercial customers. It has produced a wide variety of devices covering resist structures for testing and electroplating, and Ni molds for injection molding and hot embossing. Recent developments of this work are given in [12].

3.3. Synchrotron radiation diagnostics of devices
As synchrotron radiation from bending magnets covers a large continuous spectrum from hard X-rays to the far infrared, quite a few methods are available for diagnosing various properties of micro/nanodevices.

Refractive contrast X-ray imaging has been applied at SSLS since 2003 to characterize deep cavities in high-aspect-ratio microstructures. This method has recently been extended to include computed tomography. Fig. 6 gives an example of 3D tomography. Two snapshots of a piece of a
honeycomb structure are shown at different viewing angles in surface rendering. The honeycomb is made of SU-8 resist. Its depth is 400 μm, flat key width 50 μm, and the wall thickness 10 μm. This method obviously enables looking deeply into and through channels in high-aspect-ratio plastic microstructures as well as observing skins that are known to form at the top and the bottom of SU-8 resist layers depending on exposure parameters. It is probably the only method featuring this kind of performance. The spatial and temporal resolutions are currently about 1 μm and 1 s, respectively. SSLS is working at a modified detector that would allow sub 100 nm spatial and sub 100 μs temporal resolution.

Moreover, as shown above, infrared spectroscopy of electromagnetic metamaterials (EM3) in the THz spectral range and for the characterization of diffractive optical elements (DOE) in the near and mid infrared is also a strong diagnostic application that benefits from the brilliance of synchrotron radiation.

X-ray reflectometry that has been applied extensively to the characterization of thin film multilayer systems in terms of their thickness, density, and roughness of surfaces and interfaces [13, 14, 15] is going to be a key diagnostic tool to assess surface roughness and reflectivity of micro mirrors.

Finally, more work is underway on the in situ characterization of processes via X-ray absorption fine structure (XAFS) spectroscopy performed in micro cuvettes [16].

Fig. 6: 3D CT images of a piece of an SU-8 honeycomb in surface rendering. Flat key width of the hexagons is 50 μm, thickness of the sample 400 μm.

4. Conclusion
SSLS is using synchrotron radiation as a prime tool for the fabrication of micro/nanodevices as well as for the characterization of their properties. The benefit of this kind of comprehensive use of synchrotron radiation is highlighted by the development of cutting-edge electromagnetic metamaterials and by the refractive contrast imaging of plastic microstructures.

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