ARTICLE IN PRESS

SMM-11089; No of Pages 6

Scripta Materialia xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat

Viewpoint Article

Rolled-up nanotechnology: 3D photonic materials by design

Stefan Böttner [a], Matthew R. Jorgensen [a,*], Oliver G. Schmidt [a,b]

[a] Institute for Integrative Nanosciences, IFW Dresden, Helmholtzstr. 20, 01069 Dresden, Germany

[b] Material Systems for Nanoelectronics, Chemnitz University of Technology, Reichenhainer Str. 70, 09107 Chemnitz, Germany

ARTICLE INFO

Article history:
Received 7 March 2016
Received in revised form 20 April 2016
Accepted 21 April 2016
Available online xxxx

Keywords:
Rolled-up nanotechnology
Photonics
Microresonators

ABSTRACT

Rolled-up nanotechnology involves the deposition of strained material layers for subsequent release and relaxation into functional structures with applications spanning several disciplines. Originally developed for use with semiconductor materials, over the last decade the processes involved in rolled-up nanotechnology have been applied across a wide palette of materials resulting in applications (among others) in micro robotics, energy storage, electronics, and photonics. Here we highlight the key advancements and future directions in rolled-up photonics, focusing on the diverse demonstrations of rolled-up three-dimensional microresonators which enable integrated sensing, micro-lasing, and out-of-plane routing of light.

1. Introduction

Three-dimensional integration of microelectronic components is currently being realized in many silicon foundries, keeping pace with Moore's law which demands constantly decreasing footprints of on-chip devices. To this end designs based on stacked layers and vertical interconnects or monolithic approaches are used. Integrated optical data processing units relying on on-chip photonic components are interesting due to their speed and compatibility to standard CMOS fabrication [1], but their comparatively large size – because light can only efficiently be confined to structures with dimensions similar to the wavelength – and planar geometries make reducing their footprint an issue. Metamaterials that exploit plasmonic effects are being explored to confine light to smaller structures but require more complicated fabrication [2]. To keep the simplicity of classical optics, 3D optical integration could be a solution allowing a denser configuration of vertically integrated optical components. However, since 3D and vertical micro-optical components strongly deviate from the *status quo*, implementation requires the development of new concepts and designs. In this viewpoint paper we introduce rolled-up nanotechnology with a special focus on photonic elements and demonstrate that this technology potentially provides an interesting solution to challenges experienced in 3D photonic integration by design projects.

2. Rolled-up nanotechnology

Rolled-up nanotechnology exploits a controlled delamination and curling of strained nanomembranes or thin films that were previously deposited on a removable sacrificial layer. This process leads to the formation of folded or tubular spiral structures with diameters in the nanometer to micrometer range with wall thicknesses on the order of nanometers. Exploitation of controlled roll-up was initially employed to lattice-mismatched crystalline bilayers that subsequently folded or rolled up due to stress relaxation when the sacrificial layer was removed [3,4]. This technique was later extended to non-epitaxial methods which allowed the use of a much larger variety of materials [5]. To this end, differing thermal expansion coefficients or, more generally, different deposition parameters have been used to create differentially strained nanomembranes.

The final shape of the structures after rolling is predetermined by a photolithographic patterning and etching process of the unrolled structures. This provides a powerful tool to design and create integratable 3D structures by simple 2D photolithography on basically any available type of substrate. Using appropriate patterns, the rolling length and thus the number of rotations can be controlled because the diameter is commonly defined by the nanomembrane thickness and magnitude of the differential strain. The rolling process itself can then be started by removing a sacrificial layer which is commonly a polymer photoresist or a suitable crystalline layer that can be etched with high selectivity. More subtle design changes are possible which can locally change the tube's shape and associated properties.

The concept of rolled-up nanotechnology was quickly adopted into many different disciplines ranging from electronics, biology [6,7], photonics and beyond. For example, by rolling-up metallic/dielectric nanomembranes, capacitors [8,9], batteries [10], and even field effect transistors [11] out of single tubes have been demonstrated. A completely different field was opened up by exploiting the catalytic properties of metals such as titanium to decompose hydrogen peroxide. When combined with rolled-up technology, steerable tubular

* Corresponding author.
E-mail address: matthewrayjorgensen@gmail.com (M.R. Jorgensen).

http://dx.doi.org/10.1016/j.scriptamat.2016.04.030
1359-6462/© 2016 Published by Elsevier B.V.

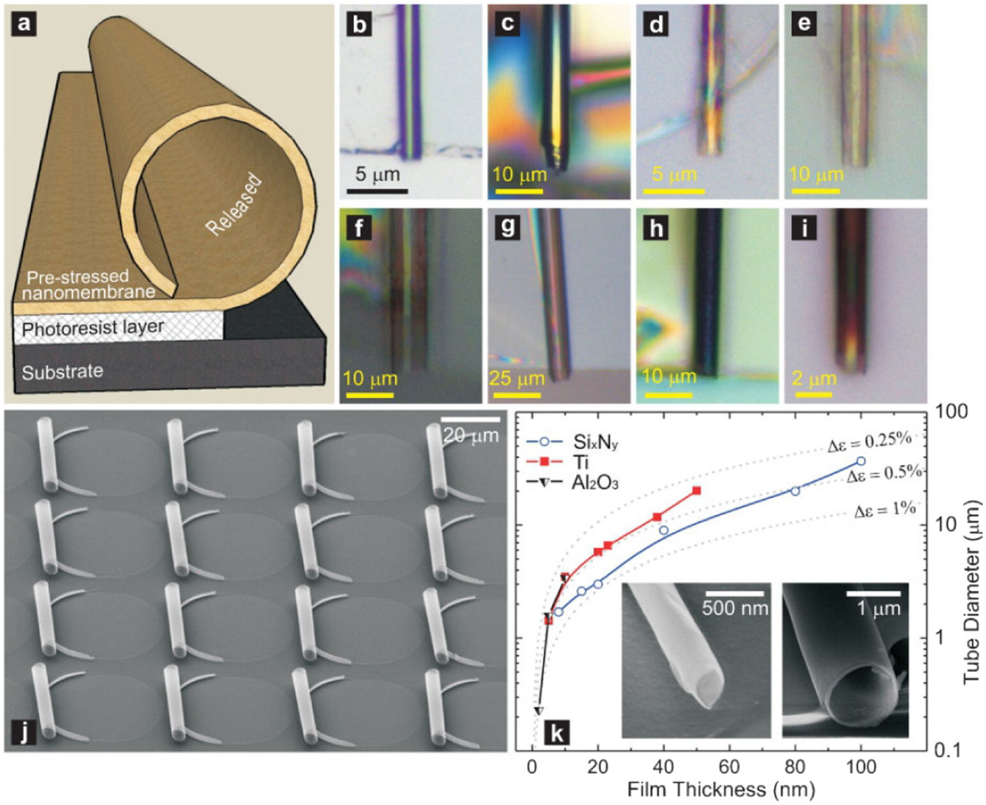

Fig. 1. (a) Schematic diagram illustrating the roll-up process of a nanomembrane into a tube on photoresist; optical images of rolled-up nanomembranes made out of (b) Pt, (c) Pd/Fe/Pd, d) TiO_2, (e) ZnO, (f) Al_2O_3, (g) Si_xN_y, (h) Si_xN_y/Ag, and (i) diamond-like carbon (DLC); (j) SEM image of an array of rolled-up SiO/SiO_2 nanomembranes; (k) tube diameters as a function of film thickness for various materials: Si_xN_y (blue open circles), Ti (red filled squares), and Al_2O_3 (black half-filled triangles). Left inset shows an SEM image of an Al_2O_3 tube with a diameter of ~230 nm. Right inset displays an SEM image of a Si_xN_y microtube. (Figure reproduced with permission from Ref. [5], © 2008 WILEY-VCH.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

microrockets or microrobots can be fabricated that thrust out oxygen bubbles to propel the tiny objects forward while magnetic fields can be used for external steering [12,13]. Furthermore, bio- and microfluidic sensors have been demonstrated that rely on the interaction of resonant light guided in the tube walls with analytes in the hollow core of the tubes [14–17]. While light is cycling around the tube walls, structural changes of the tube or refractive index changes due to the analyte are detected as spectral shifts of the resonances. The three dimensional tubular geometry is thus a great advantage as it combines a sensor with a microfluidic channel for easy integration in microfluidic systems. The 3D structure can provide a clever solution to other applications as well in the field of photonics, which is highlighted in this viewpoint article.

3. Rolled-up photonics

The 3D geometry resulting from rolled-up nanotechnology was considered as a promising structure for numerous applications spanning various fields from the very beginning [4]. However, demonstration of photonic applications developed more slowly. When the first optical investigations started, they focused on phenomena caused by strain effects and curved nanomembranes. Rolled-up nanotechnology was an ideal tool to observe such effects because epitaxial growth was the first fabrication platform used to fabricate tubes, which easily facilitated the incorporation of quantum wells and quantum dots into the tube walls. The optical emission of the wells and dots was then used to observe changes in the electronic band structure caused by the strain-mediated roll up process.

3.1. Early advances in materials and geometry

One of the pioneering works in the optical investigation of such electronic band structure changes included two GaAs/AlGaAs quantum wells embedded in a microtube with a strained InGaAs layer [18]. The quantum wells provided two internal light sources emitting light at different wavelengths which could be independently detected using a photoluminescence setup. Later strain effects were exploited to enhance optical emission by a roll-up induced transition from a type-II to type-I electronic sub-band structure [19] or to tune two epitaxial quantum dots embedded at different positions in a tube wall into spectral resonance upon pressing the tube with a tip [20].

These initial optical investigations demonstrated how rolled-up nanotechnology can enrich the field of photonics by providing a very versatile investigatory tool that can be used for a wide variety of measurements. However, these experiments did not exploit the full capabilities of the 3D geometry. Only after the wave guiding [21] and resonant properties of rolled-up microtubes were discovered [22,23] did researchers start to explore this new direction and experiments were pursued which exploit the full capabilities of 3D optical confinement in rolled-up tubes. Optical microcavities were already a well-investigated topic due to their efficient light confinement in small volumes [24]. It was therefore obvious to also probe the integratable rolled-up resonators as optical sensor devices, signal processing devices or for light matter interactions in cavity quantum electrodynamics experiments. In all mentioned applications a high value can be added by the capability of large-scale integratable fabrication.

One of the trailblazing experiments in rolled-up photonic resonators or vertically rolled-up microcavities (VRUMs) was performed by Kipp et al. and involved several improvements in design [22]. InAs quantum

Please cite this article as: S. Böttner, et al., Rolled-up nanotechnology: 3D photonic materials by design, Scripta Materialia (2016), http://dx.doi.org/10.1016/j.scriptamat.2016.04.030