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Exploiting the natural instability in thin and flexible dielectric solid films for sensing and photonic applications - INVITED

Nicoletta Granchi[1], *Luca* Fagiani[2], *Chiara* Barri[2], *Mehrnaz* Modaresialam[3], *Michele* Gherardi[2], *Angelo* Gatta Zini[2], *Benedetta Maria* Squeo[4], *Mariacecilia.* Pasini[4], *Andrea* Chiappini[5], *Laura* Pasquardini[6], *Alexey* Fedorov[7], *Marco* Abbarchi[3,8], *Maria Antonietta* Vincenti[9], *Francesca* Intonti[1] and Monica Bollani[7,*]

[1]LENS and Department of Physics and Astronomy, University of Florence, Sesto Fiorentino, Italy
[2]Department of Physics, Politecnico di Milano, Milano, Italy
[3]Aix Marseille Univ, Université de Toulon, CNRS, IM2NP Marseille, France
[4]Institute of Chemical Sciences and Technologies (SCITEC) – CNR, Milano, Italy
[5]Institute of Photonics and Nanotechnology (IFN) – CNR, Trento, Italy
[6]Indivenire srl, Trento, Italy
[7]Institute of Photonic and Nanotechnology (IFN)- Consiglio Nazionale delle Ricerche, LNESS laboratory, Como, Italy
[8]Solnil, 95 Rue de la République, Marseille, 13002, France
[9]Department of Information Engineering, University of Brescia, Brescia, Italy

Abstract. Flexible and stretchable photonics are emerging fields aiming to develop novel applications where the devices need to conform to uneven surfaces or whenever lightness and reduced thickness are major requirements. However, owing to the relatively small refractive index of transparent soft matter, these materials are not well adapted for light management at visible and near-infrared frequencies. Here we demonstrate simple, low cost and efficient protocols for fabricating $Si_{1-x}Ge_x$-based, sub-micrometric dielectric antennas with ensuing hybrid integration into different plastic supports. The dielectric antennas are realized exploiting the natural instability of thin solid films to form regular patterns of monocrystalline atomically smooth silicon and germanium nanostructures. Efficient protocols for encapsulating them into flexible and transparent, organic supports are investigated and validated. We benchmark the optical quality of the antennas with light scattering measurements, demonstrating the control of the islands structural colour and the onset of sharp Mie modes after encapsulation.

1 Introduction

Flexible and stretchable photonics are emerging fields aiming to develop novel applications where the devices need to conform to uneven surfaces or whenever lightness and reduced thickness are major requirements. However, owing to the relatively small refractive index of transparent soft matter including most polymers, these materials are not well adapted for light management at visible and near-infrared frequencies. Here we demonstrate simple, low cost and efficient protocols for fabricating $Si_{1-x}Ge_x$-based, sub-micrometric dielectric antennas with ensuing hybrid integration into different plastic supports [1]. The dielectric antennas are realized exploiting the natural mechanical instability of thin solid films to form regular patterns of monocrystalline atomically smooth silicon and germanium nanostructures that cannot be realized with conventional methods. Solid state dewetting (SSD) indeed is a natural shape instability occurring in thin solid films when heated at high temperature: it transforms a flat layer into isolated islands in a timeframe independent from the sample size [2,3].
SSD has been so far regarded as a drawback for microelectronic devices in silicon on insulator (SOI) as it limits their further size reduction. However, its potential for applications based on complex pattern formation is still unexplored in spite of the manifold advantages it offers: a) it forms monocrystalline and facetted (atomically smooth) structures (size from ~nm up to ~10 µm), free from defects and from the typical roughness produced by conventional etching methods; b) the islands are directly formed on an insulating substrate (SiO_2); c) spontaneous dewetting can produce over arbitrary scales patterns that cannot be designed numerically. Therefore, SSD can be efficiently exploited in all these fields to form perfectly ordered and complex nano-architectures on large scales, as well as randomly organized, isolated islands.

2 Results

Our samples consist of $Si_{0.7}Ge_{0.3}$ arrays of islands on a 25 nm thick SiO_2 pedestal obtained by means of electron beam lithography (EBL), reactive ion etching (RIE). After etching, the samples are cleaned by oxygen plasma for 20 min and then immersed in a 2% in vol of HF solution for 15 s to eliminate any organic contamination and oxide layer. Then, the samples are annealed at high temperatures in the 700 ◦C–800 ◦C range in the ultra-high vacuum of a

* Corresponding author: monica.bollani@ifn.cnr.it

home annealing reactor. At the end of the dewetting process, the island's height is found to vary from about 40 nm for the smaller islands up to about 90 nm for the larger ones; while, the final SiGe islands have a lateral size from 150 nm to 550 nm, which is much smaller than the initial patches etched by EBL & RIE and are electrically isolated from the substrate by the SiO_2 BOX [Fig.1]. The resulting resonators exhibit clear faceting on their surfaces which can be ascribed to [001], [111] and [113] crystalline planes and an average aspect ratio (AR), which is defined as the ratio between height and radius (R), of 0.6.

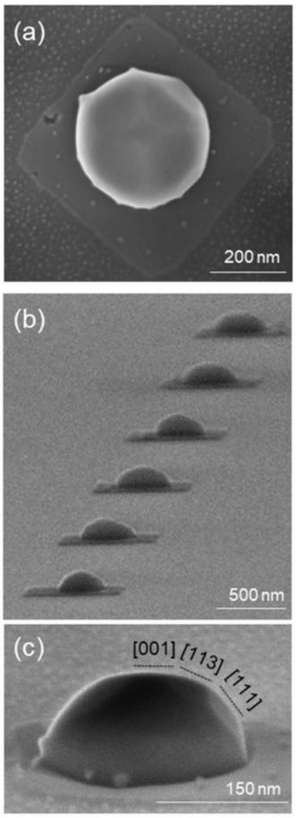

Figure 1 a) SEM top view image of a single dewetted Si0.7Ge0.3 island. (b) SEM image of islands acquired with a tilt angle of 45 degrees with respect the sample normal to highlight the faceting of each scatterer. (c) SEM image of of a single island, where the faceting planes {001}, {113} and {111} are labelled.

These dewetted materials are then used as master by a hybrid top-down/bottom-up approach based on sol-gel dip-coating and nano-imprint lithography for the faithful reproduction of the disordered hyperuniform metasurfaces in plastic materials [4]. Efficient protocols for encapsulating them into flexible and transparent, organic supports are investigated and validated. We benchmark the optical quality of the dielectric antennas with light scattering measurements [5,6], demonstrating the control of the islands structural colour and the onset of sharp Mie modes after encapsulation [1]. Dark-field spectra fit quite well the theoretical peaks [Fig.2]. As expected, the smaller island (bottom panel) exhibits only the ED/MD type resonance, while the bigger one shows two main peaks, MQ ($\lambda \approx 570$ nm) and ED/MD ($\lambda \approx 650$ nm). Deviations between the theoretical and simulated spectra can be attributed to the fact that FEM simulation does not consider imperfections of the resonator shape induced by the dewetting instability. Thanks to the ease of implementation of our fabrication methods, these results are relevant for the integration of SiGe-based dielectric Mie resonators in flexible substrates on large surfaces.

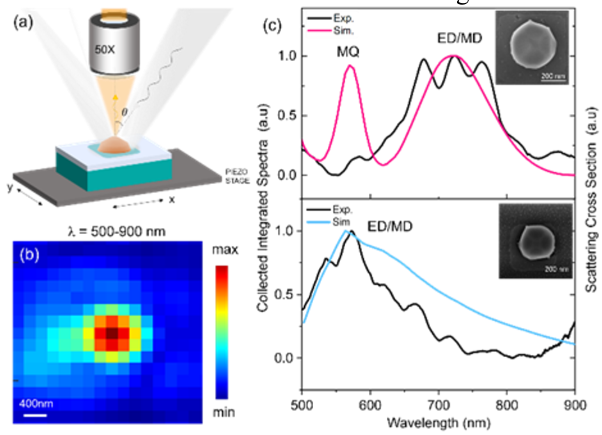

Figure 2 a) Sketch of the Dark-field scanning setup. b) Hyperspectral map of an island with R ≈ 190 nm filtered around the wavelength range 500-900 nm. c) Comparison between the collected integrated spectra and the simulated scattering cross section for island of R ≈ 190 nm (upper panel) and R ≈ 80nm (lower panel).

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