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Solid state dewetting of semiconductor thin films: from fundamental studies to photonic applications

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Abstract. Here we propose to exploit the natural instability of thin solid films, i.e. solid state dewetting, to form regular patterns of monocrystalline atomically smooth Si, $Si_{1-x}Ge_x$ and Ge nanostructures that cannot be realized with conventional methods. Additionally, the solid-state dewetting dynamics is guided by pre-patterning the sample by a combination of electron-beam lithography and reactive-ion etching, obtaining precise control over number, size, shape, and relative position of the final structures. Methods and structures will be optimized towards their exploitation mainly in photonic devices application (e.g. anti-reflection coatings, colour-filters, random lasers, quantum emitters and photonic sensors).

Solid state dewetting (SSD) is a natural shape instability occurring in thin solid films when heated at high temperature: it transforms a flat layer in isolated islands in a timeframe independent from the sample size [1]. The potential of SSD for microelectronic and photonic 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) templated dewetting from simple patterns leads to more complex, monocrystalline and ordered architectures, with the additional advantage of reduced etching time with respect to conventional lithographic approaches; d) spontaneous dewetting can produce over arbitrary scales patterns that cannot be designed numerically. Therefore, SSD can be efficiently exploited in several fields, including high-density magnetic recording media [3], flexible photonics [4], photocatalysis [5] or dielectric Mie resonator [6], to form perfectly ordered and complex nano-architectures over large scales, as well as randomly organized, isolated islands.

Among the dewetting systems reported in the literature, in our group Si and $Si_{1-x}Ge_x$ dewetting, i.e. Si or SiGe structures directly formed on an electrically insulating and optically transparent substrate (mainly SiO_2), has been efficiently exploited to realize Mie-resonator arrays of nanostructures with typical footprint ranging from few nm up to several µm [7-10].

Additionally, by a proper combination of e-beam lithography (EBL) and reactive ion etching (RIE) processes, we can realize dewetted nanostructures that can play as Mie resonators [8,10]. One of the main key features of high-refractive-index dielectric Mie resonators is that their optical spectra display strong electric and magnetic resonances and, by changing the geometrical parameters of the particles, the spectral positions of both the resonances can be tuned independently. As a building material for such resonators, Si or $Si_{1-x}Ge_x$ particles are very promising, being their absorption losses very weak in the optical and near-infrared range of frequencies. Furthermore, on the contrary to plasmonic nanoparticles made of gold or silver, they are compatible with silicon-based nanofabrication technologies being, therefore, more appealing for low-cost production. The layout obtained is reported in Fig. 1.

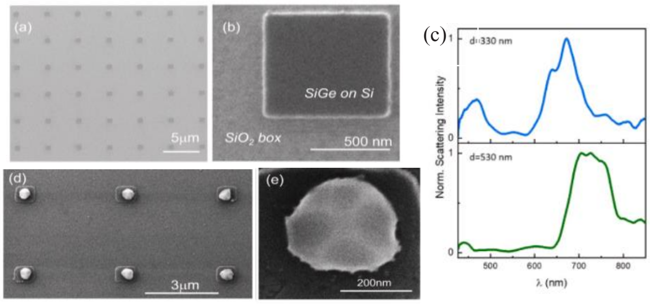

Fig. 1: SEM images of original SiGe patterns (a-b), normalized dark-field spectra of SiGe dewetted islands with two different sizes (c) and SEM images of the SiGe structures after annealing (d-e). Adapter from [10].

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In contrast with more conventional top-down fabrication approaches where only cylinders can be obtained, this method enables a true 3D shaping of the islands, that act as Mie resonators [6,9,10].

Evidence in the linear regime of bright Mie-type localized resonances is reported in the visible spectral range [10], with a spectral position that can be tuned by modifying the size of the nanoparticles (Fig. 1-c).

Additionally, investigation of dewetting mechanism for germanium thin films will be proposed. Germanium is a material of particular interest for photonic devices working at near and mid-infrared frequency. Therefore, the study and validation of a low-cost processing of Ge-based film, such as SSD, is of considerable interest for this kind of applications. Furthermore, thanks to its larger surface energy, Ge dewetting can be typically achieved at sensibly lower temperature with respect to Si, opening up the possibility to process this material exploiting simpler experimental set-ups. Despite the relevance of this material for photonics, the investigation of its dewetting features has not been extensively studied and a deep understanding of the process has been recently proposed by our group [11]. In particular, we followed the morphological and structural properties of the dewetted Ge islands during different annealing treatments (Fig. 2).

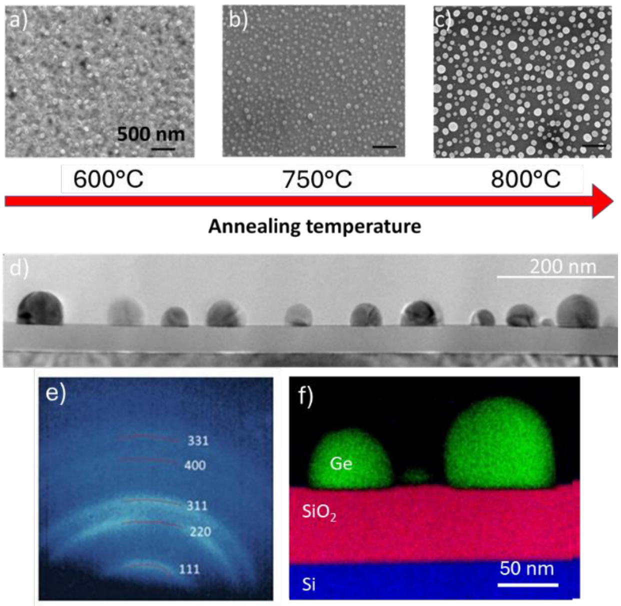

Fig. 2: SEM images of an a-Ge sample, initial thickness of 10 nm, annealed for 15 minutes at 600°C a), 750 °C b), and 800°C c). Complete dewetting achieved in c). HR-TEM image of Ge crystalline island obtained by the annealing treatment of 15 minutes at 800°C d). RHEED image obtained for dewetted islands obtained for 800°C annealing e). EELS chemical map of the Ge-island dewetted at 800°C for 15 min f). Adapted from [11].

By a combination of in-situ reflection high-energy electron diffraction (RHEED) during low and high-temperature annealing, the initial crystallization dynamics of the Ge film has been clarified, and the structural characterization of the dewetted islands has been disclosed by high-resolution transmission electron microscopy (HR-TEM), atomic force microscopy (AFM) and scanning electron microscopy (SEM). Chemical composition has been assessed by electron energy loss spectroscopy (EELS). Different initial a-Ge film thickness (range: 10 nm–200 nm) and annealing treatments have been investigated to control the dewetting process. Finally, we extended the solid state dewetting process up to 20 cm wafers showing the possibility to tune particles size varying the initial a-Ge thickness of the deposited film, highlighting the scalability of the process. Beyond fundamental understanding of the a-Ge dewetting process, these results are relevant for the fabrication of large-scale hard masters for nanoimprinting lithography and novel photonic platforms fabricated via a scalable, lithography-free, CMOS-compatible process.

Here, the work purpose is therefore to present the properties of dewetted Si, SiGe and Ge islands and to exploit them to produce flexible films for photonic applications. In this regard, an innovative approach to transfer SiGe and Ge dewetted islands into a flexible substrate such as polydimethylsiloxane (PDMS) will be presented. Finally, these results are relevant for the integration of SiGe- and Ge-based dielectric Mie resonators in flexible substrates over large surfaces that can be used as a novel sensoristic photonic platform. Indeed, upon proper functionalization, the presented SiGe- and Ge-Mie resonators, can act as bacteria sensors.

References

1. F. Leroy et al., Surface Science Reports **71**, 2, 391-409 (2016).
2. M. Naffouti et al., Science Advances **3**, 11, eaao1472 (2017).
3. Y. J. Oh, et al., Small **5**, 860–865, (2009).
4. A. Benali et al., J. Phys : Photonics **2**, 015002, (2020).
5. M. Altomare et al., Chem Sci **7**(12), 6865-6886, (2016).
6. N. Granchi et al., Opt Express **31**, 5, 9007, (2023).
7. M. Bollani et al., Nature Comm **10**, 5632, (2019).
8. M. Abbarchi et al., Microelectronic Engineering **190**, 1-6, (2018).
9. N. Granchi et al., APL Photonics **6** (12), 126102 (2021).
10. L. Fagiani et al., Opt. Mat. X, **13**, 100116, (2022).
11. S. Freddi at al., Materials Science in Semiconductor Processing **174**, 108228 (2024).

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