High resolution, hybrid 3D topography fabrication using grayscale electron beam lithography

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In consumer electronics, micro-optics and surface engineering there is a demand for lateral and at the same time vertical high-resolution, discrete-stepped and continuous-profile patterns. Typical applications are diffractive or hybrid refractive-diffractive optical elements, which are used for example in backlight displays, optical projections for pattern recognition or as complex lens systems for arbitrary and customized beam shaping[1]. Despite improvements in laser direct writing[2] and 2-photon-lithography[3], electron beam lithography (EBL) is still the method of choice for grayscale patterns spanning scales from a few microns down to a few nanometers when it comes to resolution and precision. Such patterns can be in addition combined with selective thermal reflow.[4]

We evaluated several positive tone resists for EBL grayscale patterning ranging from poly (methyl methacrylate) (PMMA) (Fig. 1) to the commercial systems ZEP520A (Zeon Corp.) and mr-PosEBR (micro resist technology GmbH). We realized further a wide variety of features for refractive and diffractive optics, microfluidics as well as hierarchical, bioinspired patterns (e.g. Fig. 2). The tested resists showed a huge potential for grayscale patterning itself. Additionally, as their thermoplastic behavior allows for a controlled selective reflow of exposed features, this enhances the feature variety even further. Grayscale EBL and reflow can be applied on all feature sizes from the micro to the nano range: We realized for example grayscale patterns in PMMA down to the 'single-digit' regime (Fig. 3).

We found universal, meaning material independent, rules for grayscale patterning and reflow: (i) The deeper a pattern is buried into a resist the more sloped is the sidewall angle (Fig. 4) due to competing development fronts and lateral development. (ii) This angle between two different steps follows always the same governing principles. Further, technological combinations with nanoimprint lithography were demonstrated, e.g. in ZEP520A. (iii) Thermal reflow is a surface-energy driven creep process. This was simulated with an efficient continuum-model based on soap-films requiring only a minimum set of known material properties (surface tension and mobility/viscosity) (Fig. 5).[4]

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[2] D. Radtke and U. D. Zeitner, Optics Express (15) 2007, 1167-1174.

[3] J. Fischer and M. Wegener, Laser Photon. Rev. (7) 2013, 22-44.

[4] R. Kirchner and H. Schift, J. Vac. Sci. Technol. B (32) 2014, 06F701.

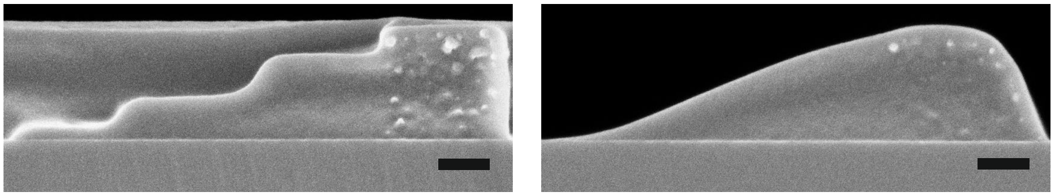

Fig. 1: SEM micrographs of patterns in a 500 nm thick PMMA layer: a) 5-level multistep grayscale pattern after exposure and development and b) after selective thermal reflow for 120 min at 120°C.

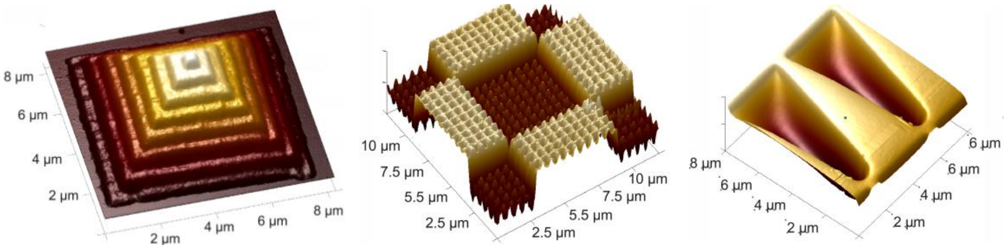

Fig 2: AFM micrographs of grayscale patterns realized by exposure and development: a) 9 level pyramid in 2 µm thick PMMA film, b) hierarchical nano-on-micro pattern in a 500 nm spin-on-glass film and c) tapers with ultra-smooth continous profile in 2 µm thick PMMA film after selective thermal reflow of a multistep pattern for 5 min at 130°C.

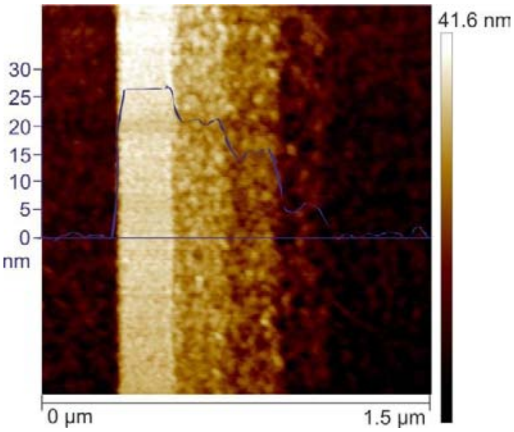

Fig. 3: 5-level pattern in a 27 nm thick PMMA film featuring 6 nm high 'single-digit' steps

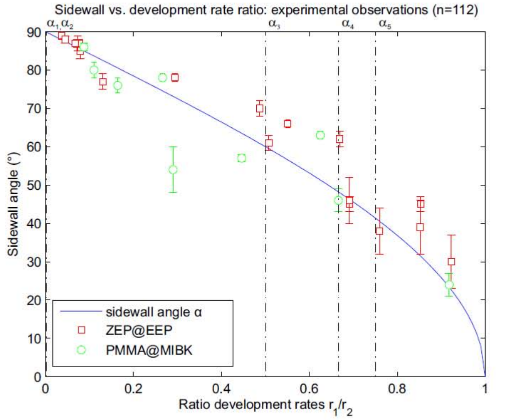

Fig. 4: Universal (material and process independent) behavior of the step-to-step sidewall angles for a 5-level pattern as depicted in Fig. 1a and 3.

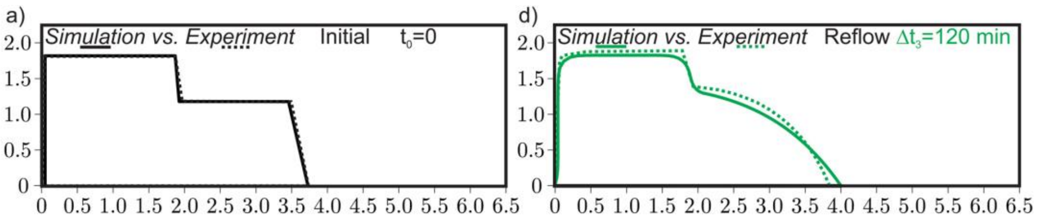

Fig. 5: Simulation of the reflow process using a soap-film model giving a good agreement between the simulated and the experimentally confirmed profile: a) before and b) after reflow for 120 min at 110°C.