Selective profile transformation of electron-beam exposed multilevel resist structures based on a molecular weight dependent thermal reflow

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Grayscale electron-beam lithography (EBL) is commonly used to generate multilevel resist structures in poly(methyl methacrylate) (PMMA). As has been shown in our previous work, a local variation in the molecular weight (M_w) does not only lead to a dose dependent development rate, but also to differences in glass transition temperature (T_g) [1], which enables a selective reflow of the exposed areas at temperatures around the original T_g, while the non-exposed areas remain unaffected. Thus both structures with sloped (up to 45° inclination) and vertical sidewalls can be created [2]. In this contribution we present further advances towards more structural variation in one single resist structures. Due to a combination of two exposure and development steps with a different dose range, we are able to create similar stepped structures but with different M_w. Therefore, upon thermal treatment the transformation of multilevel structures into continuous slopes can be exclusively restricted to specific patterns while other exposed structures stay unaltered. This allows the fabrication of entirely novel 3-D resist profiles, with smooth slopes as well as stepped resist contours on the same substrate and in very close vicinity to each other.

The process scheme is described in Figure 1: Two grayscale EBL steps are applied to a PMMA layer on a silicon substrate, each followed by a development step which thins the resist at the exposed areas with a dose-dependent etch rate. Firstly, a multilevel pattern is created using a low dose which results in a rather low reduction of the M_w and hence a long development time. Afterwards, an additional stepped structure is created using a second exposure with a higher dose and consequent development step. The development of resist exposed during the first EBL step is completed in two stages: partially straight after the first exposure and finally after the second one. The duration of the first stage is reduced by the time required for the second development step. The dose variation during EBL exposure results in a different M_w and consequently different T_g of the two stepped resist pattern. Thus, if a thermal reflow is applied using an adequate temperature in the range of T_g, the stepped structure exposed to higher doses is selectively transformed into a sloped profile while other exposed areas maintain their original stepped shape.

The selective profile transformation is illustrated in Figure 2. Here, a 1050 nm high PMMA resist was two-step exposed and developed according to the procedure described above. The subsequent reflow of a polymer ridge at 110 °C for 120 min results in a continuous slope at one side and a multilevel pattern on the other side of the ridge. The AFM profile characterization in Figure 3 shows that the reflowed slope exhibits a smooth surface with an inclination of ~ 22° while the non-reflowed steps are still clearly distinguishable. In order to make such 3-D patterns also available for other materials, the resist structures were transferred into the silicon substrate by proportional RIE and thus 3-D stamps were fabricated, e.g. for nanoimprint applications [3]. They can serve as test stamps for comparison between stepped and sloped structures, e.g. for diffraction optical elements.

[1] H.R. Keymeulen et al., *J. Appl. Phys.* **102** 013528 (2007).
[2] A. Schleunitz and H. Schift, J. Micromech. Microeng. **20**(9)(2010) 095002.
[3] H. Schift, *J. Vac. Sci. Technol. B* **26**(2) 458-80 (2008).

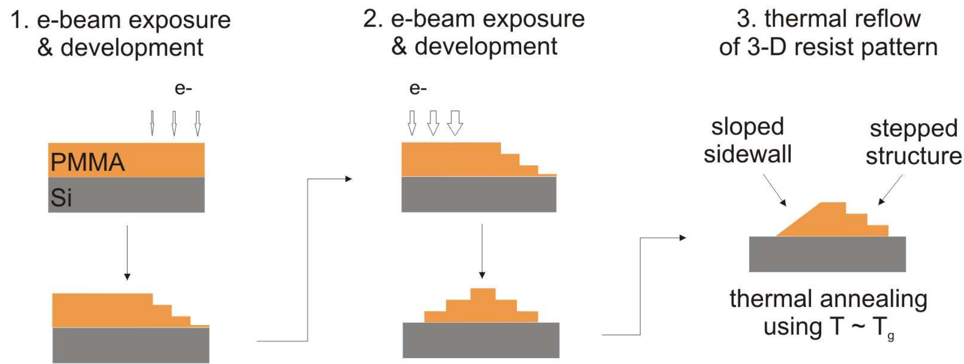

Figure 1 A two-step grayscale EBL is successively applied to a PMMA layer. The resist is selectively transformed from a stepped into a sloped profile based on a M_w dependent thermal reflow.

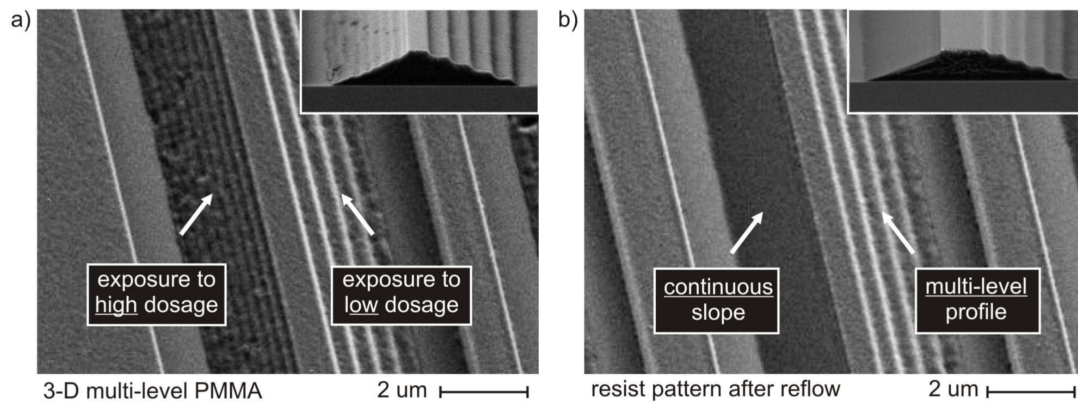

Figure 2 (a) SEM micrographs of a double-exposed PMMA multi-level pattern. The 500 nm wide steps (5 levels) were exposed prior to the 250 nm wide steps (9 levels). (b) Upon thermal reflow, the stepped profile exposed to higher dose (left side) is transformed into a continuous slope while the lower-dose pattern stays unaltered (right side).

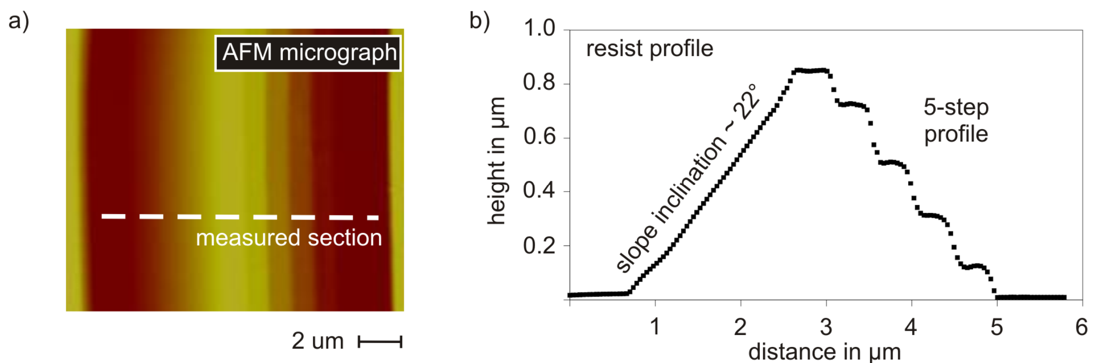

Figure 4 Profile of a polymer ridge after reflow by AFM. Due to the M_w dependent T_g, the resist shows stepped (high M_w) and sloped (low M_w) contours in close vicinity.