Thermo-mechanical probe lithography at 500 kHz pixel rate

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Thermo-mechanical scanning probe lithography offers several attractive features over the current de-facto standard in maskless nano-fabrication, electron beam lithography (EBL). The resist layer is removed locally and directly without further development steps by bringing a heated probe into contact with the resist (schematic in Figures 1a and 1b). The heated tip thermally activates the depolymerisation reaction and evaporates the resulting monomers[1]. In addition, the patterning depth can be controlled independently for each pixel, giving this technology inherent 3-D patterning capability[2]. Metrology for qualification is carried out *in-situ*, using the same probe in imaging mode. This 'direct development and inspection' process makes turnaround between writing and qualifying a pattern virtually instantaneous, allowing time savings of the order of magnitudes compared to current processes. Here, we report the acceleration of our probe-based lithography process to 500 kHz. Imaging can be done at similar rates, hence we demonstrate a lithographic process with an unprecedented turnaround time (patterning, development, metrology) of the order of minutes.

In the first stage, the mechanics of the set-up were designed to achieve required scan speeds while preserving positioning accuracy. Direct-drive 100 µm scanners with a nominal resonance frequency of 4 kHz were used for high-speed actuation and fine positioning. A feed-forward control method was implemented to reduce the position error to less than 10 nm at 10 mm/s scan speeds.

With the robust and accurate mechanical setup in place, the polymer resist layer and cantilever actuation were optimised to achieve a 500 kHz write pixel rate. A 10 nm thick layer of poly-phthalaldehyde was used for patterning. A pre-tension-and-release strategy was used to actuate the cantilever above its resonance frequency of 150 kHz. Figures 2a and 2b (close up) show the small and large scale patterning fidelity and resolution at a pixel rate of 500 kHz and a scan speed of 7.5 mm/s.

Imaging is done using the thermo-electric read method. In order to determine the resolution-speed tradeoff, the modulation transfer function (MTF) was measured using a grating pattern read at varying speeds (0.1 - 24 mm/s). As expected, the main roll-off and -3 dB point (25k lines/s) is determined by the thermal time constant of the cantilever (6 µs). Deconvolving the image and ther-mal decay time of the cantilever increased the -3 dB point by a factor of 4, to 100k lines/s.

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[1]O. Coulembier *et al.*, Macromolecules, **43**, 572 (2010);
H. Ito and C. G. Willson, Polym. Eng. Sci.*,* **23**, 331(1983); **23**, 1018 (1983)
[2]D. Pires *et al.*, Science, **328**, 732(2010)
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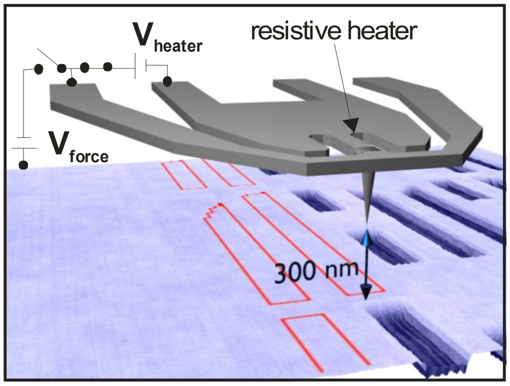

Figure 1a: Probe tip floating above surface; no interaction with polymer. The resistive heater heats the tip to ca. 700°C

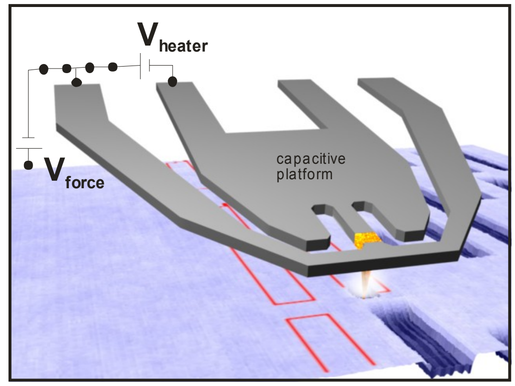

Figure 1b: A voltage applied between cantilever and substrate results in a force across the cantilever-substrate capacitor. This brings the tip into contact with the poly-phtalaldehyde, and allows depth control. The resist decomposes and evaporates locally where heated.

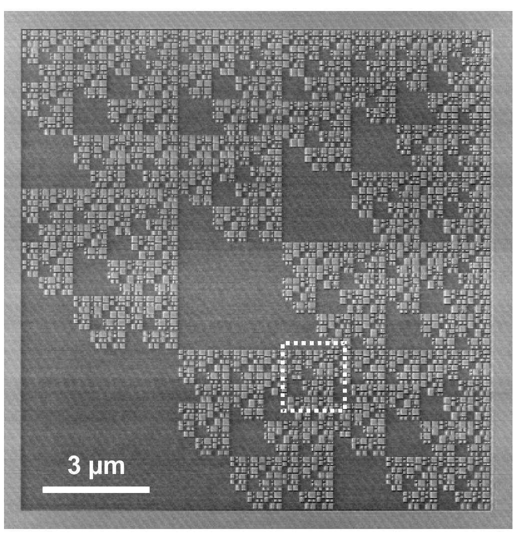

Figure 2a: Fractal carpet pattern written into 10 nm poly-phtalaldehyde at 500 kHz pixel rate; 880 x 880 pixels, 15 nm pixel pitch, ~5 nm depth, 13.2 x 13.2 µm overall size, linear write speed 7.5 mm/s, overall write duration < 12 s

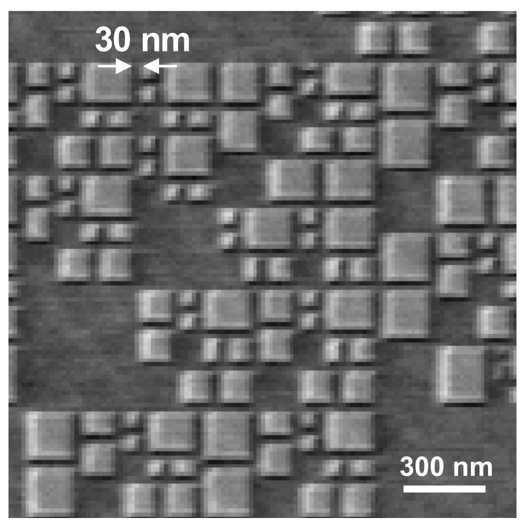

Figure 2b: 1.5 x 1.5 µm close up of the area marked in Figure 2a