Silicon Mold Improvement by Hydrogen Annealing for Low-loss PIC Fabrication Utilizing Nanoimprint Lithography

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Compared to fiber systems, Photonic Integrated Circuits (PICs) offer higher integration density, ultra-high speed, and lower power consumption. These advantages make PICs highly promising for widespread applications in data processing, communications, and quantum photonics. In such systems, low-loss waveguides are critical for performance[1]. As the fundamental component of PICs, waveguides largely dictate overall circuit loss, with sidewall roughness, which closely links to lithography and etching processes and is a key source of scattering loss.[2] Thus, reducing waveguide sidewall roughness is essential.

Nanoimprint lithography (NIL), which has volume production and low cost with high resolution, has been considered to fabricate PIC. During NIL process, the sidewall roughness is determined by mold roughness. However, spatial frequency response of sidewall roughness of different mold smoothing process is different. Hydrogen annealing reduces silicon surface roughness at high temperature and hydrogen adsorption, which lowers surface energy and allows atoms to migrate from peaks to valleys[3]. Although the physical mechanism of hydrogen annealing is well understood, there has been no analysis of how hydrogen annealing can reduce the roughness at spatial frequencies, which is significant for the evaluation NIL fabrication process of PIC waveguide loss.

Here, we fabricated silicon mold with and without hydrogen annealing, and analysis them with SEM image processing. By comparing the power spectral density (PSD) of the sidewall roughness of silicon mold, we found out during hydrogen annealing process the roughness special frequency around 100 to 1000 nm has been suppressed. The SEM image of the silicon mold within and without hydrogen annealing is shown in Figure 1, and PSD roughness of silicon mold within and without hydrogen annealing is shown in Figure 2. The analysis of the

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[1] Gaeta, Alexander L., Michal Lipson, and Tobias J. Kippenberg. "Photonic-chip-based frequency combs." *nature photonics* 13.3 (2019): 158-169.

[2] Roberts, Samantha, et al. "Measurements and Modeling of Atomic - Scale Sidewall Roughness and Losses in Integrated Photonic Devices." *Advanced Optical Materials* 10.18 (2022): 2102073.

[3] Lee, M-CM, et al. "Thermal annealing in hydrogen for 3-D profile transformation on silicon-on-insulator and sidewall roughness reduction." *Journal of Microelectromechanical systems* 15.2 (2006): 338-343.

waveguide patterned by silicon mold with and without hydrogen annealing after NIL and etching is still ongoing.

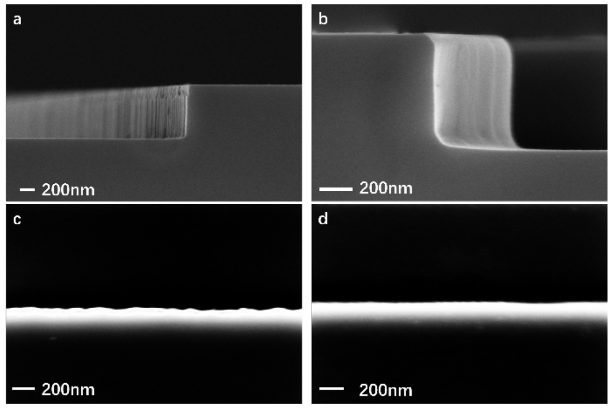

Figure 1: SEM image of silicon mold with and without hydrogen annealing: (a) Cross section of silicon mold without hydrogen annealing. (b) Cross section of silicon mold after hydrogen annealing. (c) Top view of silicon mold without hydrogen annealing. (d) Top view of silicon mold with hydrogen annealing.

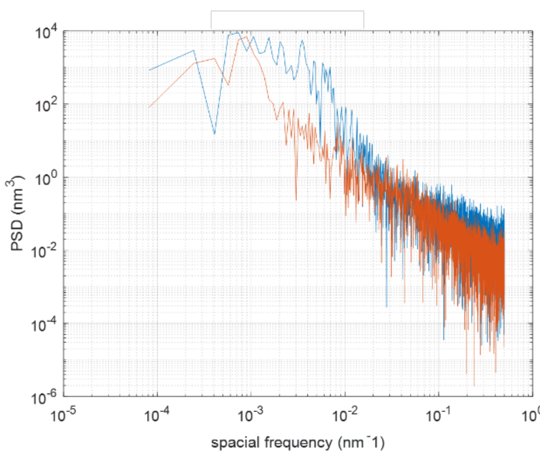

Figure 2: Power Spectrum Density roughness of silicon mold sidewall with and without hydrogen annealing: The blue line is the PSD roughness without hydrogen annealing and the orange line is PSD roughness after hydrogen annealing.