Supplementary Information

Ultra-high-aspect-ratio structures through silicon using infrared laser pulses focused with axicon-lens doublets

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Figures: S1 – S8

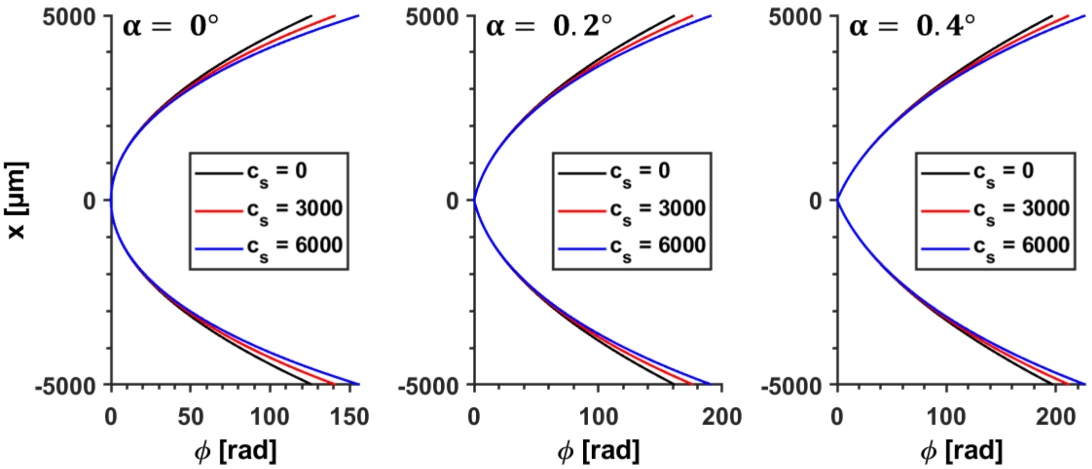

Fig.S1: Accounted phase-profiles in the simulations for different combinations of axicon-lens doublets. Each phase-profile adds three contributions: a spherical-phase describing focusing with lens of focal length f = 400 mm, a non-spherical curvature to describe the effect of spherical aberration with strength c_s, and a conical phase to describe the effect of an axicon of base-angle $\alpha = 2°$.

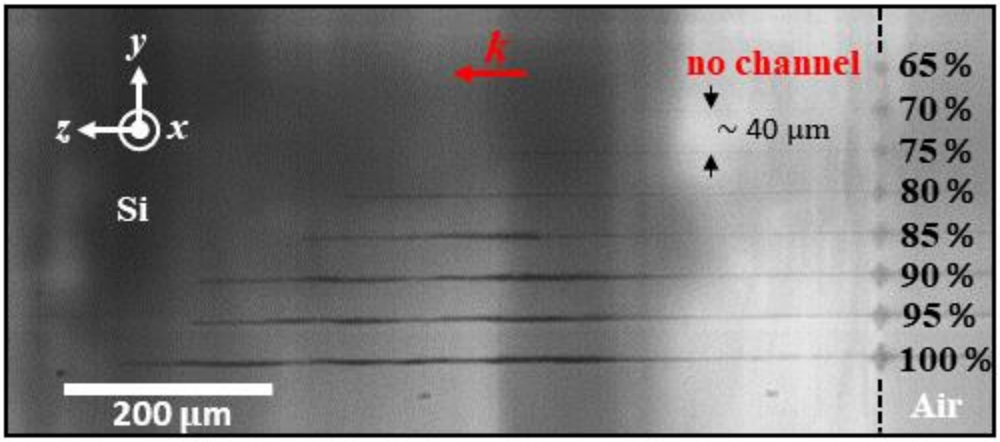

Fig.S2: Induced microchannel modifications with pseudo-Bessel micro-beams inside c-Si at varying pulse energy (E). The modifications are written with repeated irradiations (N = 20,000) of picosecond pulses. Focusing depth is fixed at 600 µm under the wafer surface (indicated by black dashed line). The apparent modification threshold is estimated to be 12.9 µJ (at 70%). 'k' indicates the writing laser propagation direction. Separation between the adjacent microchannels is 40 µm.

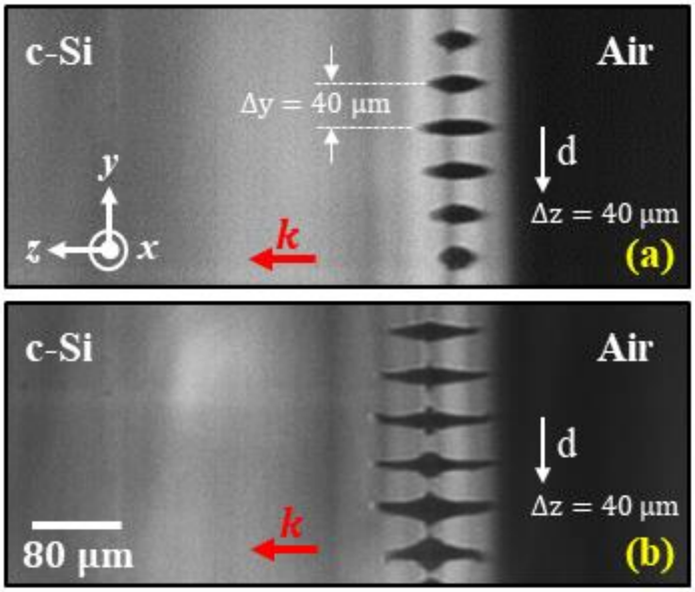

Fig.S3: Modification responses at varying depth (*d*) inside c-Si when focusing – (a) picosecond laser pulses with an objective lens of NA 0.45, and (b) femtosecond pseudo-Bessel beam with an axicon-lens doublet (objective: NA 0.45, axicon: $\alpha = 2°$). Laser conditions: $E = 18.5$ µJ, and $N = 20{,}000$ pulses. Both cases show no deep-bulk-modifications except damages in the vicinity of the surface entrance. Δy and Δz are the laser-writing intervals along *y* and *z* directions, respectively.

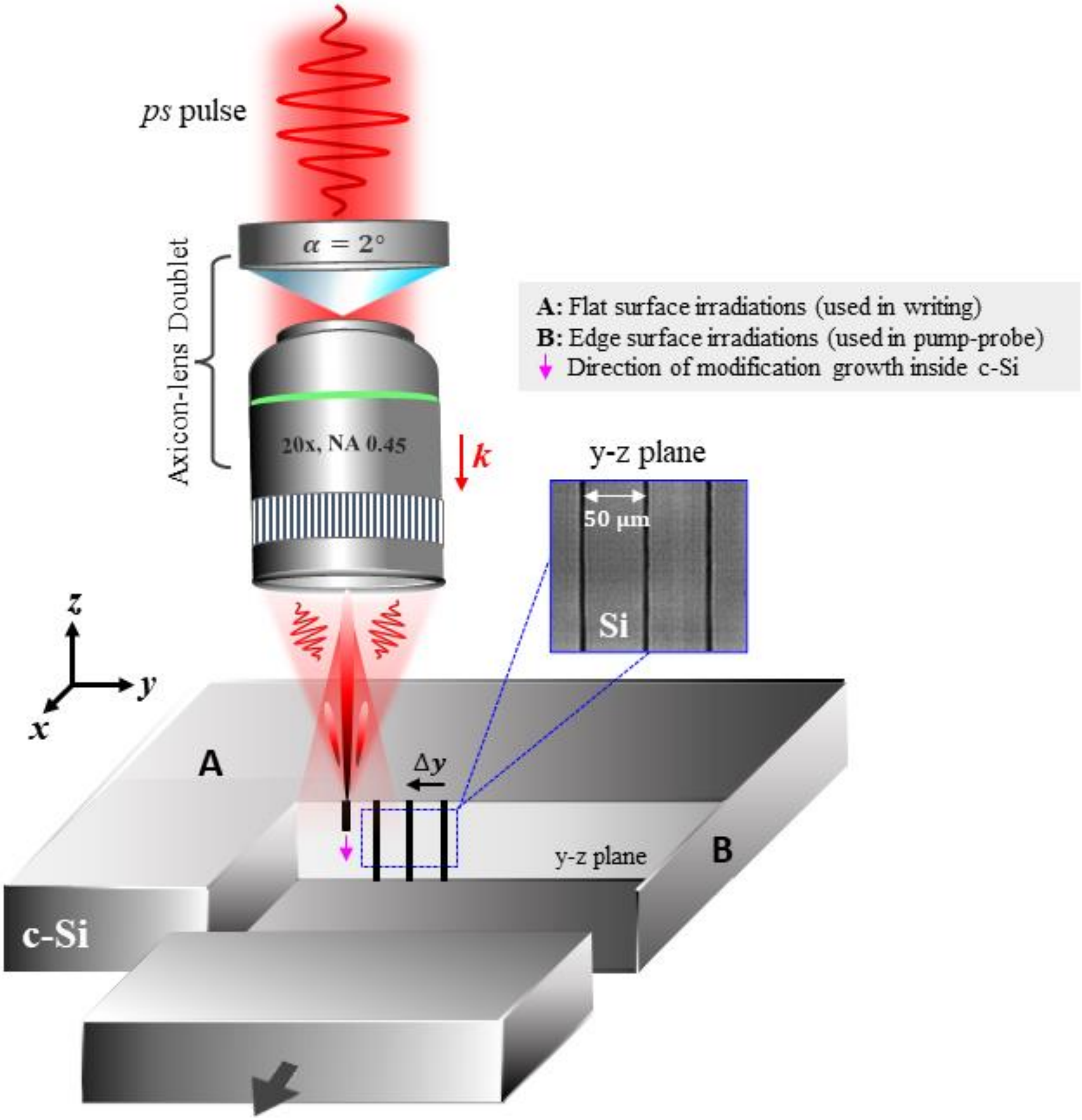

Fig.S4: Schematic of the writing arrangement to fabricate high-aspect-ratio microchannels through c-Si with percussion writing modality. The top flat surface (A) of the sample is considered for laser-irradiations. Inset: Cross-sectional view (y-z plane) of the produced structures inside c-Si as observed by infrared transmission microscopy system. Δy indicates the separation between adjacent microchannels set at 50 μm in this specific case. More configuration details are given in the main text (see section '*Experimental setup*').

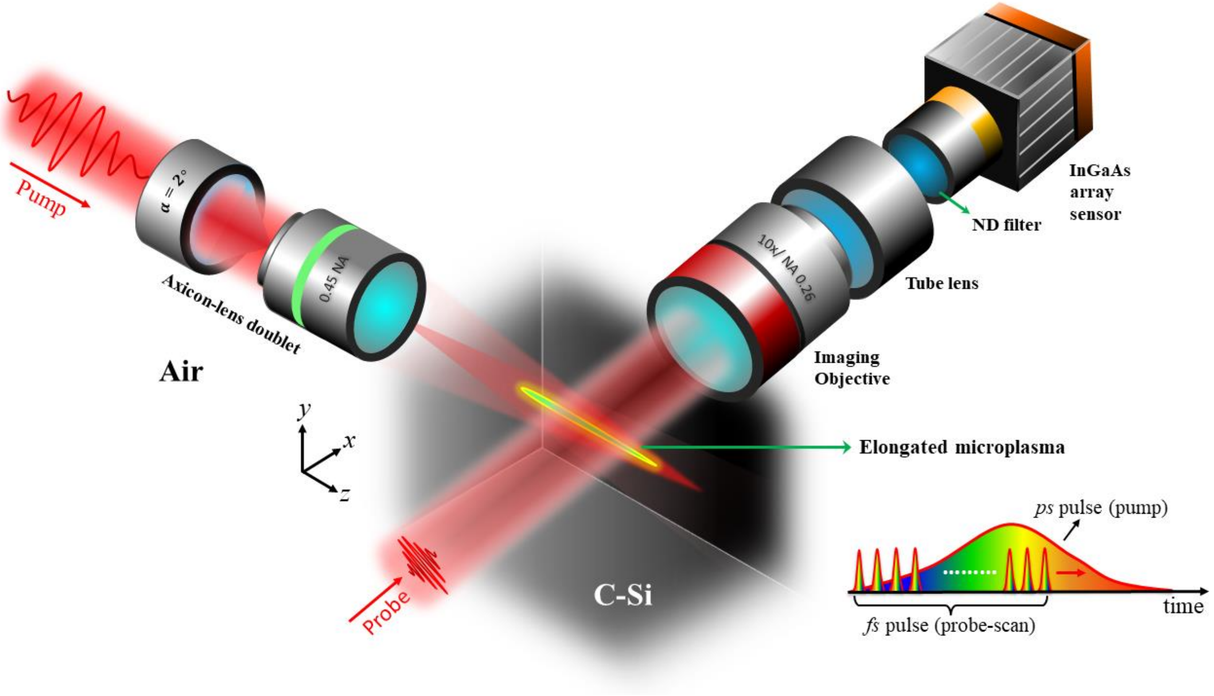

Fig.S5: Schematic of the experimental geometry used for pump-probe measurement to study the ionized-microplasma associated energy coupling of the pseudo-Bessel micro-beams within the bulk of c-Si. The delayed fs-probe pulse is used for the *in-situ* observations of the spatio-temporal dynamics of the elongated microplasma channels induced by the picosecond and femtosecond pumps, respectively. The narrow 1-mm thick edge surface (B) of the sample is considered for laser-irradiations. More configuration details are given in the main text (see section '*Experimental setup*').

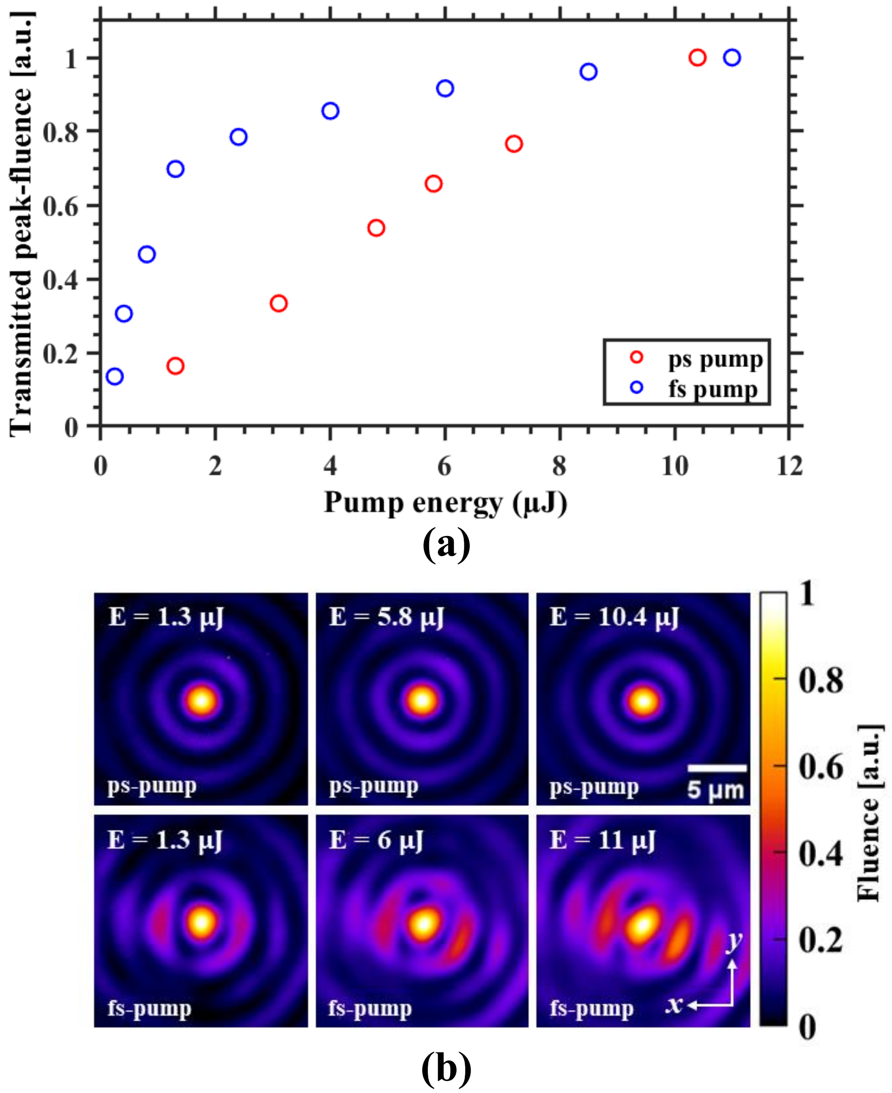

Fig.S6: (a) Transmitted peak-fluence (normalized to maximum) as a function of the pump energy (*E*), for different pump-irradiation conditions. Measured values correspond to the peak-signal levels of the pseudo-Bessel beam-focus as imaged with a microscope at the flat back surface of the 1-mm thick c-Si sample. While the picosecond pump exhibits an almost linear increase of the peak-fluence, the femtosecond pump experiences an important clamping due to strong nonlinear pulse-distortion and plasma effects inside c-Si. (b) Corresponding profile images of the pseudo-Bessel beam-focus measured at the flat back surface of the c-Si wafer, showcasing the beam-distortions in the case of the femtosecond pump at high *E* values (~11 μJ), whereas the beam profiles associated to the picosecond pump is almost unaffected with the equivalently increasing value of *E*. These results confirm that the picosecond pump is less prone to nonlinear interaction effects inside c-Si. Each image is normalized with respect to its peak-fluence level.

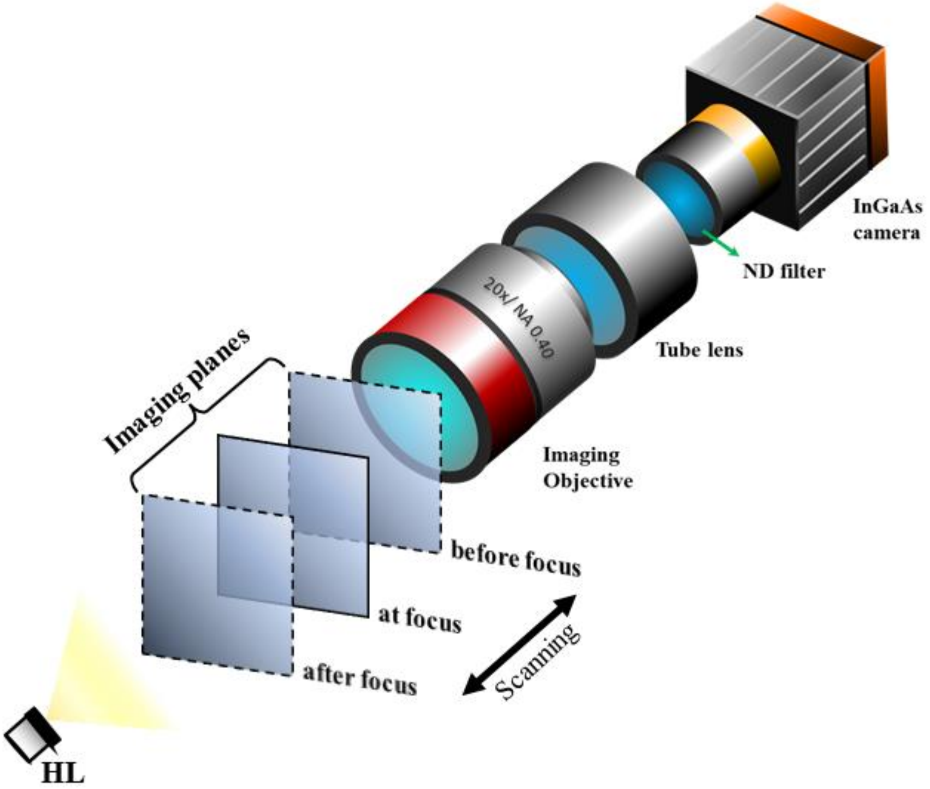

Fig.S7: Schematic of the high-resolution infrared transmission microscopy system to record shadow-images of the microchannels formed in the bulk of c-Si. Shadow-images are taken with 20x magnification, at different imaging-focusing-depths to retrieve useful optical information linked with the written structures. Illumination source is a halogen lamp (HL).

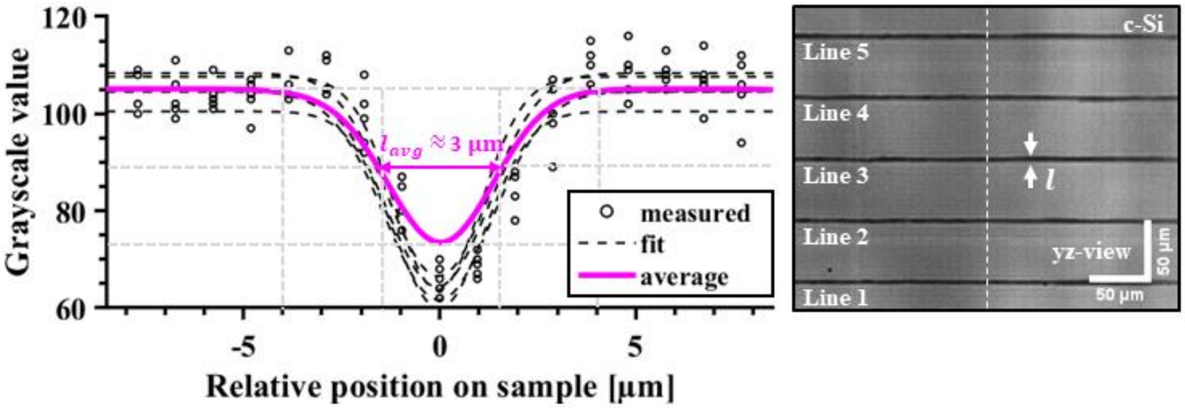

Fig.S8: Lateral profiles of the written microchannels inside c-Si obtained by focusing 50-ps infrared laser pulses using axicon-lens doublet under identical condition at d = 600 µm, E = 18.5 µJ and N = 20,000 pulses. Inset represents the measured IR transmission microscopy image of those reproducible microchannels. Only the central part of the fabricated channels is shown here.