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Ultimate limitations in the performance of kinoform lenses for hard x-ray focusing: supplementary material

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This document provides supplementary information to "Ultimate limitations in the performance of kinoform lenses for hard x-ray focusing," https://doi.org/10.1364/optica.6.000790. Diffractive x-ray lenses suffer from limited focusing efficiency, which can be improved by replacing the binary nanostructures of the lenses with kinoforms. Here we present the first example of kinoform lenses for x-ray and compare their efficiency with those of binary Fresnel zone plates (FZPs) realized through gray-scale focused Xe ion beam lithography. Unexpectedly, experimental results indicate lower focusing efficiencies of kinoform lenses compared to binary FZPs between 5-7keV. Simulations that include absorption reveal that kinoform lenses can only provide a limited boost in the diffraction efficiency in multi-keV x-ray energies and for impractical lens thicknesses. Combined with significant challenges in kinoform lens fabrication, the modest gains of this approach may suggest that it is not the path to increase focusing efficiency.

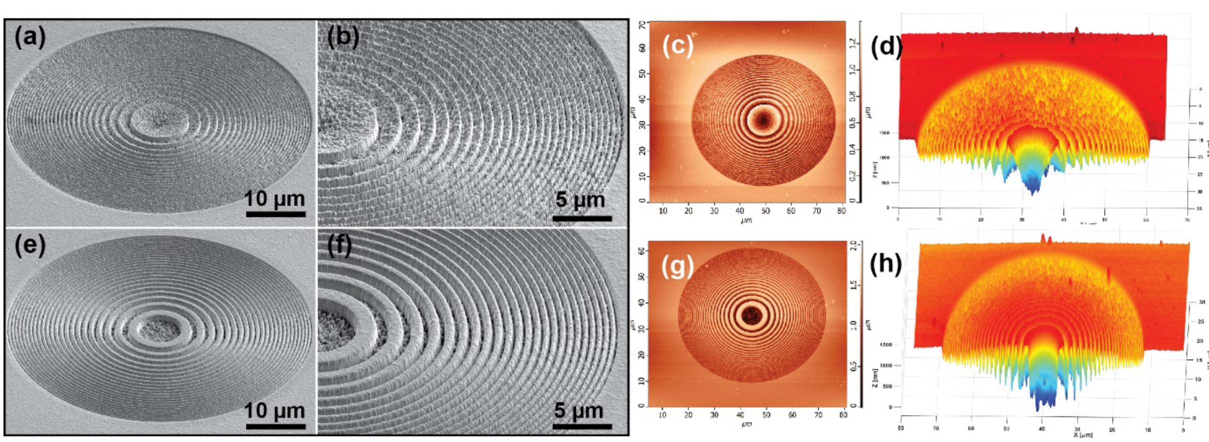

Fig. S1. W kinoform and binary FZP lenses. (a-d) and (e-h) Kinoform lenses and binary FZP milled in W, respectively. (c-d)and (g-h) Atomic force microscopy measurements of the lens profile highlighting the innermost zones in kinoform and binary FZP, respectively. The AFM tip shape introduced the usual systematics into the measured height profiles.

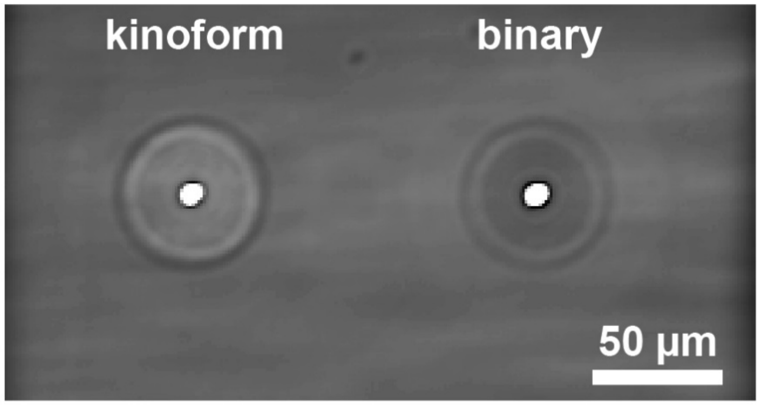

Fig. S2. Mapping of intensity at the focal plane of Au kinoform (left) and binary FZP (right) lenses by scanning a 10-µm pinhole with a 1-µm sampling interval. The resulting intensity map is a convolution of the probe and the intensity profile. Finely sub-1-µm focused intensity is sampled multiple times by the displaced large 10-µm probe resulting in the apparent plateau of bright intensity at the focal spot.

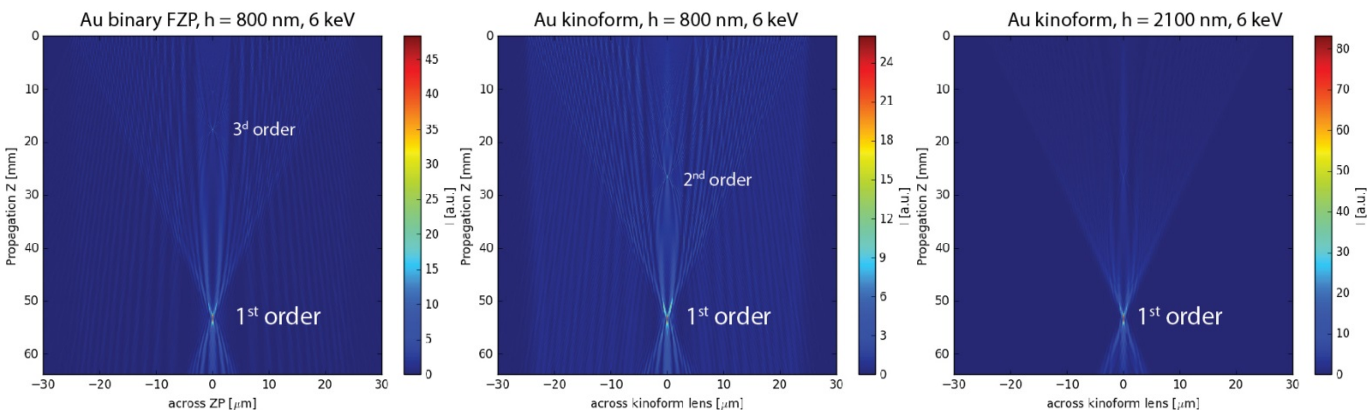

Fig. S3. Simulation of wavefront propagation. (Left) Intensity of 6 keV X-ray beam after a binary FZP with outermost zone width of 220 nm and zone height of 800 nm. This height is close to optimal in terms of efficiency for the selected energy, lens design and lens material. (Center) Intensity of 6 keV X-ray beam after a kinoform lens with outermost full-period width of 440 nm and zone height of 800 nm. This height is not optimal in terms of efficiency for the selected energy, lens design and lens material. (Right) Intensity of 6 keV X-ray beam after a kinoform lens with outermost full-period width of 440 nm and zone height of 2100 nm. This height is close to optimal in terms of efficiency for the selected energy, lens design and lens material.

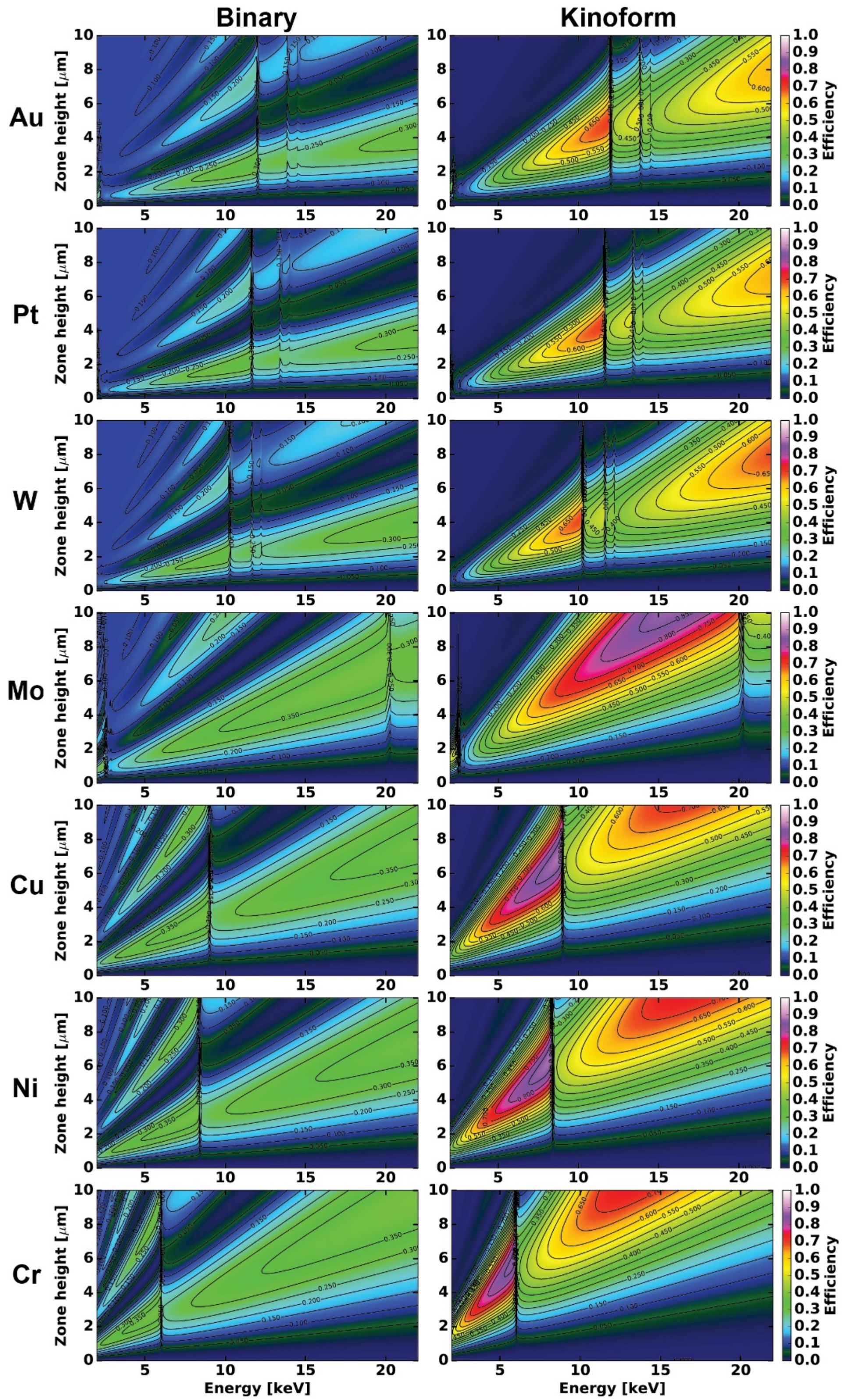

Fig. S4 Calculated 1st order efficiencies (isolines) of binary FZPs and kinoform lenses made of a variety of materials for hard X-rays focusing. Bulk material densities were assumed in the calculations (Au -19.32 g cm^{-3}, Pt – 21.45 g cm^{-3}, W - 19.3 g cm^{-3}, Mo - 10.22 g cm^{-3}, Cu - 8.96 g cm^{-3}, Ni - 8.9 g cm^{-3}, Cr - 7.19 g cm^{-3}).

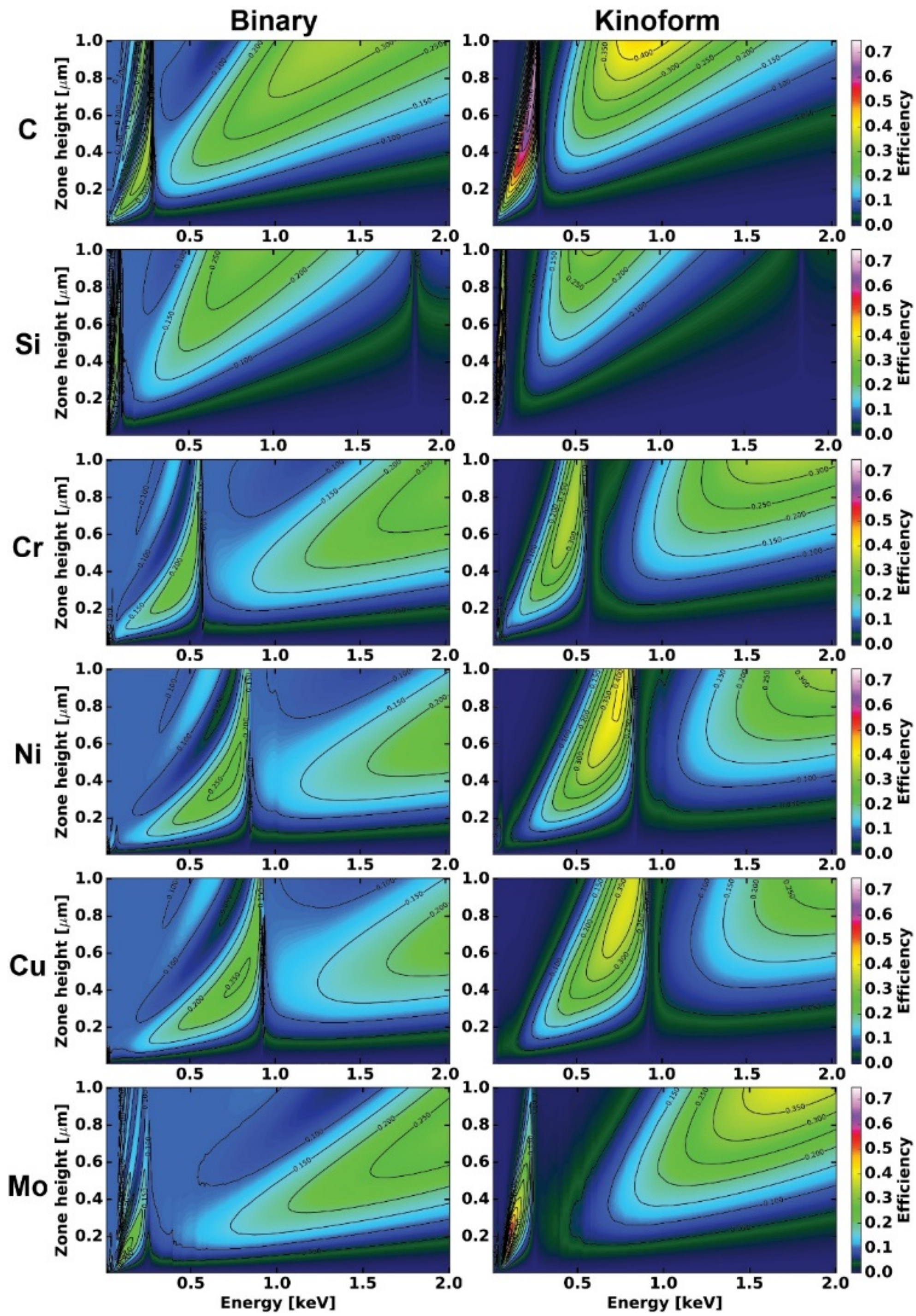

Fig. S5. Calculated 1st order efficiencies (isolines) of binary FZPs and kinoform lenses made of a variety of materials for soft X-rays focusing. The C lenses are calculated assuming the density of diamond and bulk densities for other materials (C - 3.5 g cm^{-3}, Si - 2.33 g cm^{-3}, Cr - 7.19 g cm^{-3}, Ni - 8.9 g cm^{-3}, Cu - 8.96 g cm^{-3}, Mo - 10.22 g cm^{-3}).

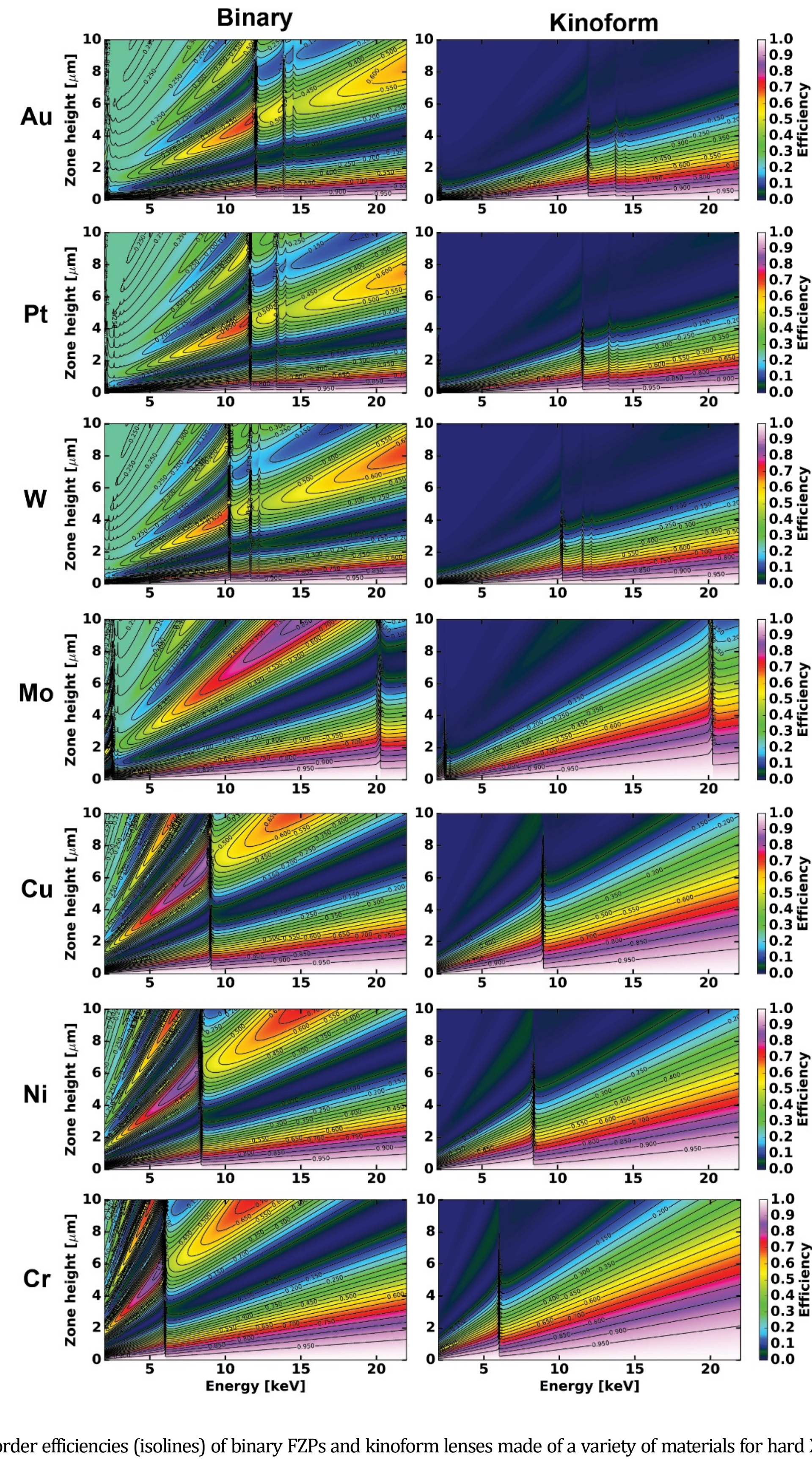

Fig. S5 Calculated 0th order efficiencies (isolines) of binary FZPs and kinoform lenses made of a variety of materials for hard X-rays focusing. Bulk material densities were assumed in the calculations (Au -19.32 g cm-3, Pt – 21.45 g cm-3, W - 19.3 g cm-3, Mo - 10.22 g cm-3, Cu - 8.96 g cm-3, Ni - 8.9 g cm-3, Cr - 7.19 g cm-3).

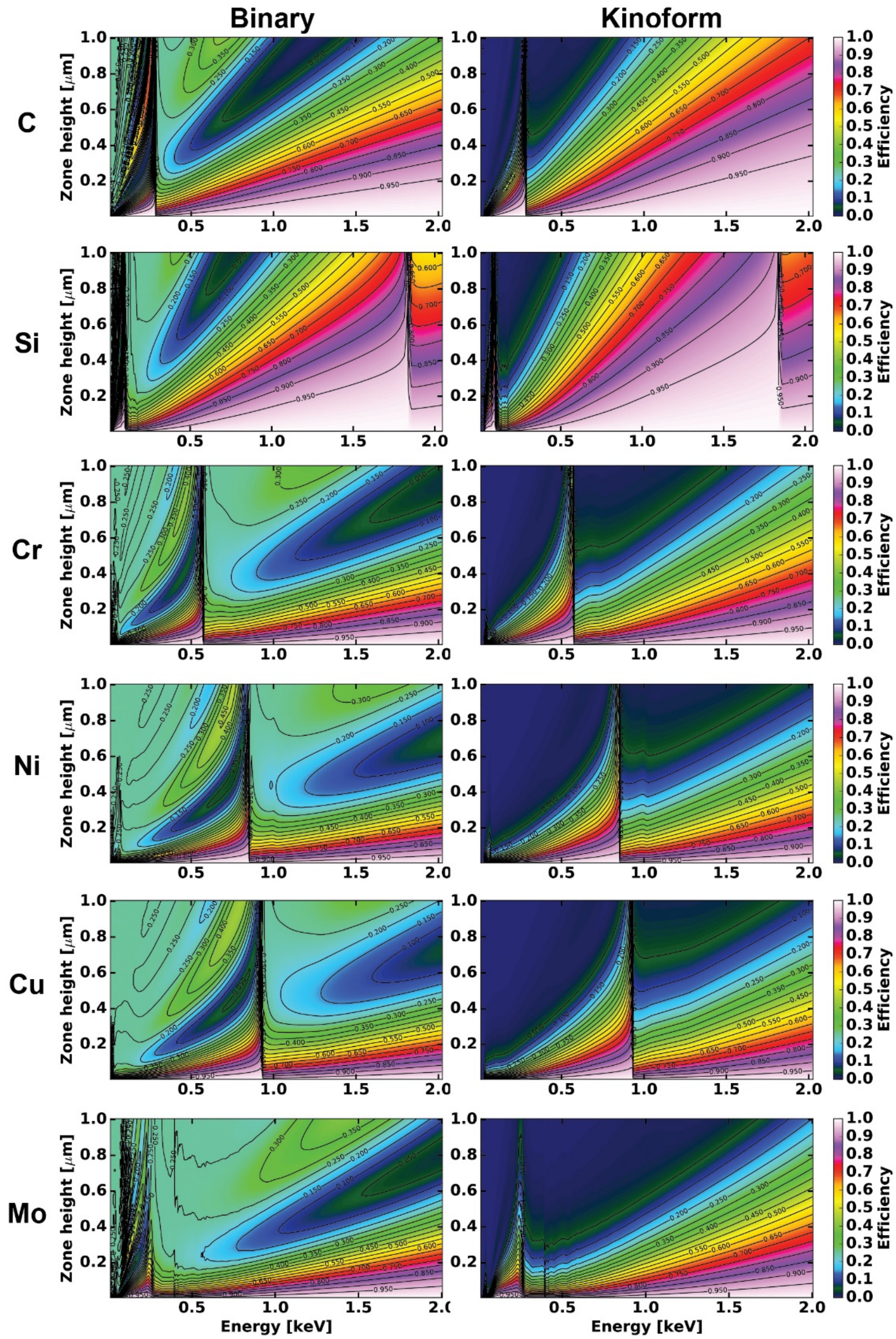

Fig. S6 Calculated 0th order efficiencies (isolines) of binary FZPs and kinoform lenses made of a variety of materials for soft X-rays focusing. The C lenses are calculated assuming the density of diamond and bulk densities for other materials (C - 3.5 g cm^{-3}, Si - 2.33 g cm^{-3}, Cr - 7.19 g cm^{-3}, Ni - 8.9 g cm^{-3}, Cu - 8.96 g cm^{-3}, Mo - 10.22 g cm^{-3}).