Supporting Information: A Simulation Model for Direct Laser Writing of Metallic Microstructures Composed of Silver Nanoparticles

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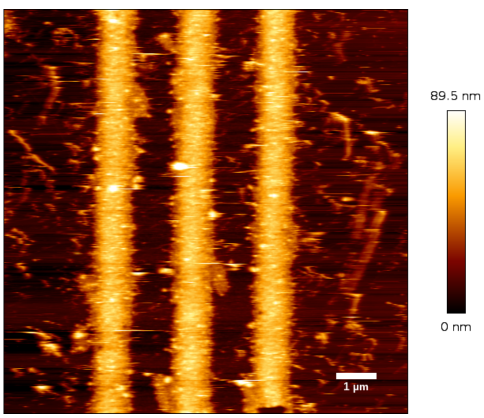
Here we provide more detailed information about the properties of the structures that were fabricated using Metal Direct Laser Writing. First, we show the AFM images of the samples. Second, we give the averaged values for line width, height, and root-mean-square (RMS) roughness.

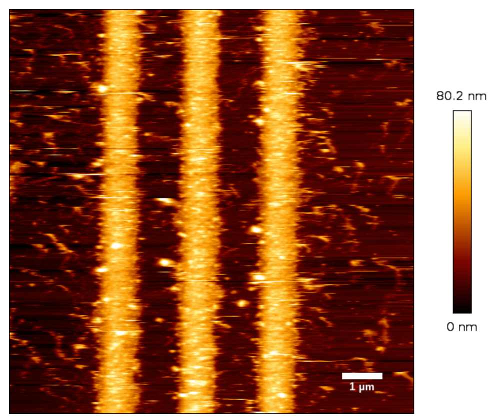
1 AFM height maps of silver lines fabricated with MDLW

For analysis of experimental deposition rates, samples were produced using three different objectives with numerical apertures NA=0.3, NA=0.8, and NA=1.4. As the laser focus becomes smaller with growing NA, the finest lines are obtained using the highest possible NA. Because the refractive index of the photoresist is lower ($n \approx 1.33$) than that of immersion oil, only a reduced effective NA is achieved, e.g., using the NA=1.4 objective results in an effective NA=1.2.

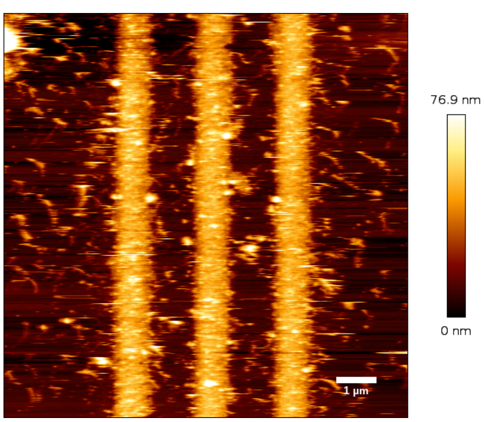
The diagonal patterns as well as the bright spots that are visible on some samples, e.g., Figure S3e, stem from the scanning of the AFM and are not related to the MDLW fabrication process.



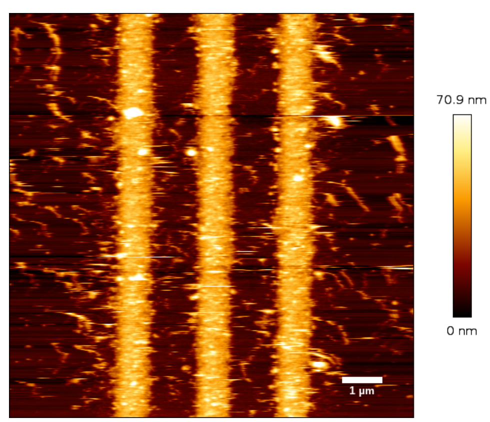
(a) $3\,\mu\mathrm{m\,s^{-1}}$



(b) $5\,\mu\mathrm{m\,s^{-1}}$

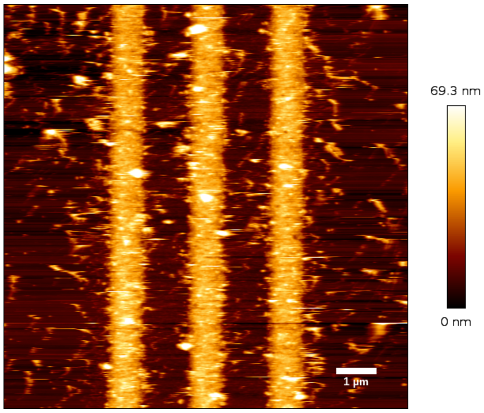


(c) $7\,\mu\mathrm{m\,s^{-1}}$

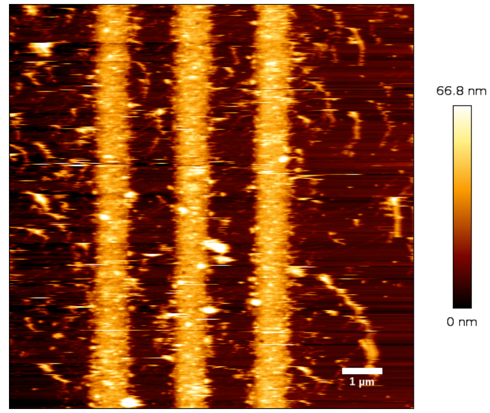


(d) $9\,\mu\mathrm{m\,s^{-1}}$

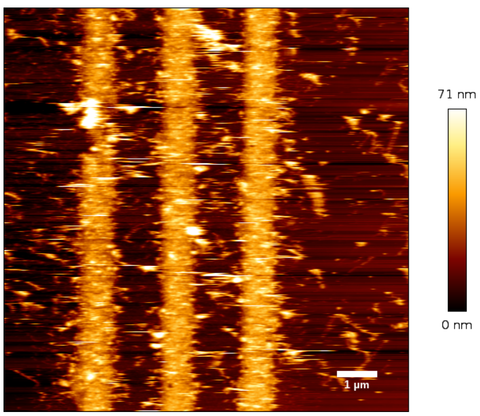
Figure S1: AFM height maps of silver lines written with NA=1.4 objective. Laser wavelength $\lambda = 780\,\mathrm{nm}$, pulse repetition rate 80 MHz, time-averaged laser power $P_0 = 6.3\,\mathrm{mW}$, scanning speeds $v = 3\ldots21\,\mu\mathrm{m\,s^{-1}}$



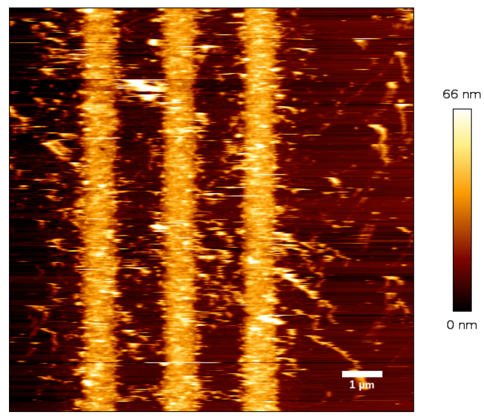
(e) 11 µm s^{-1}



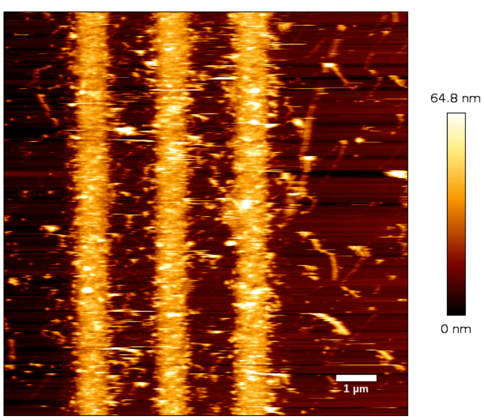
(f) 13 µm s^{-1}



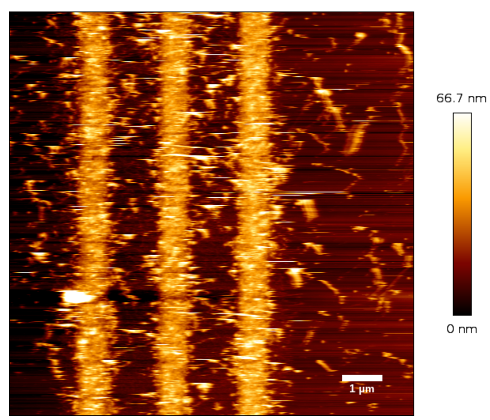
(g) 15 µm s^{-1}



(h) 17 µm s^{-1}

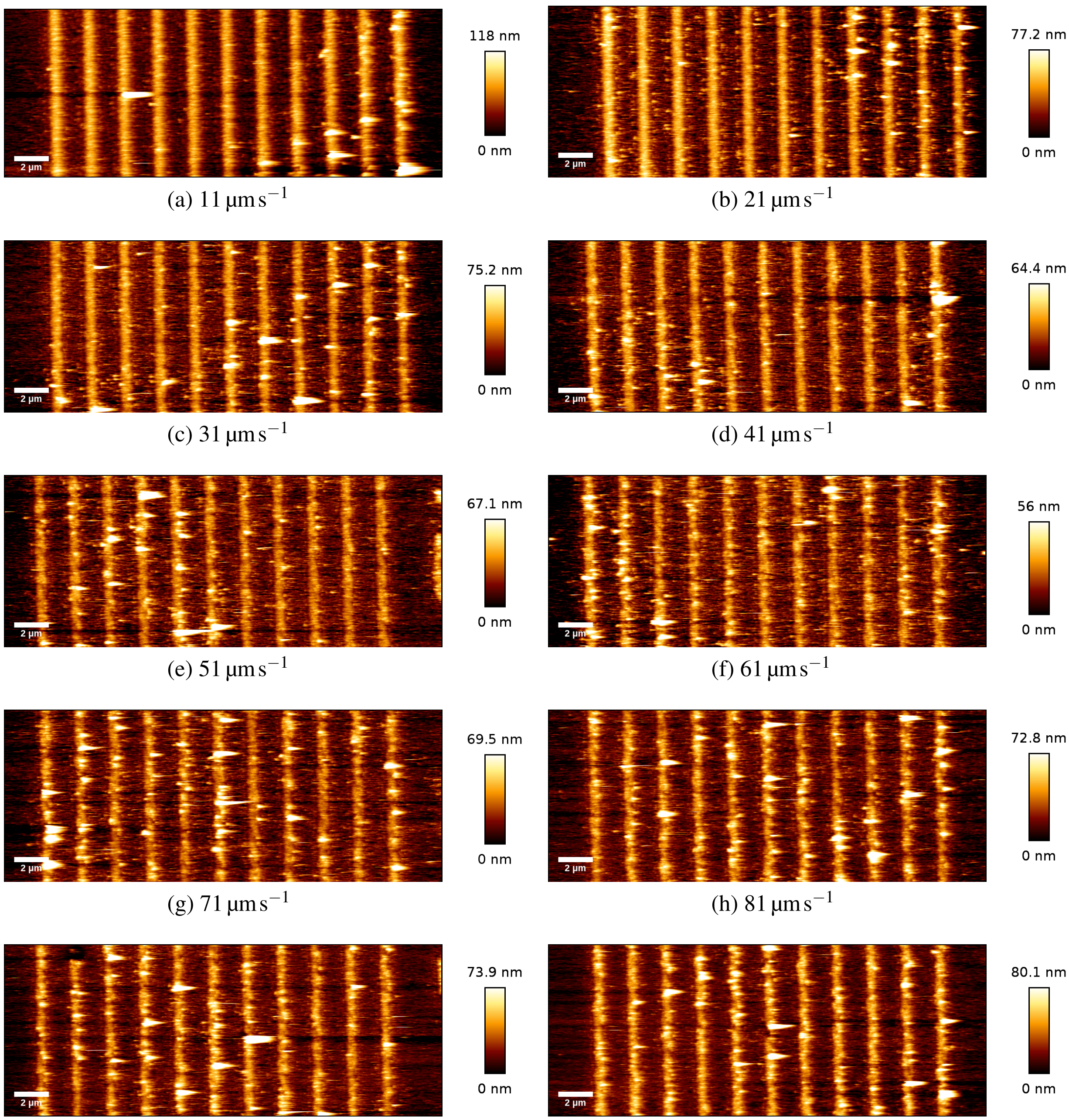


(i) 19 µm s^{-1}



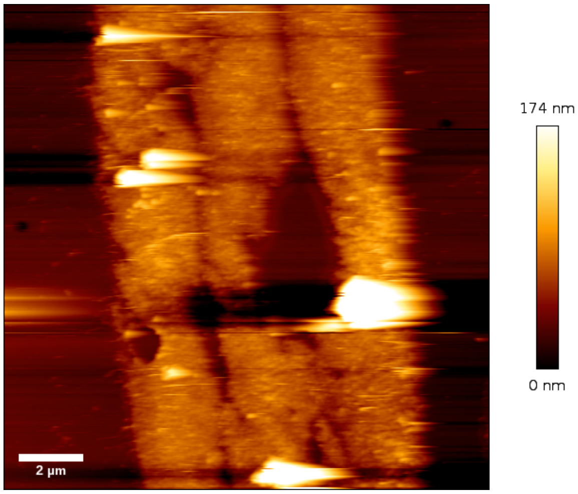
(j) 21 µm s^{-1}

Figure S1: (Continued)AFM height maps of silver lines written with NA=1.4 objective. Laser wavelength $\lambda = 780$ nm, pulse repetition rate 80 MHz, time-averaged laser power $P_0 = 6.3$ mW, scanning speeds $v = 3 \ldots 21$ µm s^{-1}

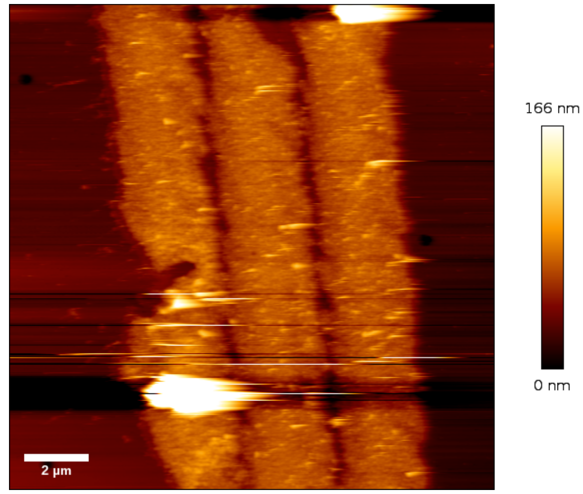


(a) 11 $\mu m\,s^{-1}$
(b) 21 $\mu m\,s^{-1}$
(c) 31 $\mu m\,s^{-1}$
(d) 41 $\mu m\,s^{-1}$
(e) 51 $\mu m\,s^{-1}$
(f) 61 $\mu m\,s^{-1}$
(g) 71 $\mu m\,s^{-1}$
(h) 81 $\mu m\,s^{-1}$
(i) 91 $\mu m\,s^{-1}$
(j) 101 $\mu m\,s^{-1}$

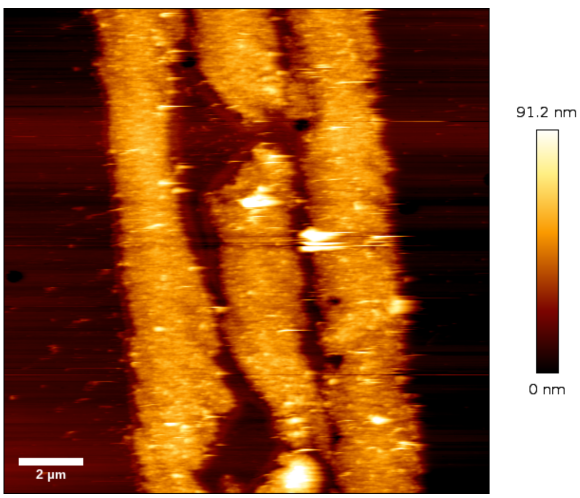
Figure S2: AFM height maps of second run with NA=1.4, written at higher scanning speeds of 11…101 $\mu m\,s^{-1}$. Laser wavelength 780 nm, pulse repetition rate 80 MHz, time-averaged laser power 3.4 mW.



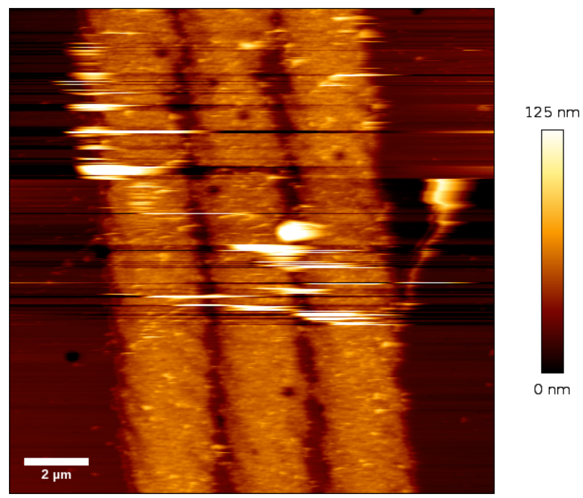
(a) 3 $\mu m\,s^{-1}$



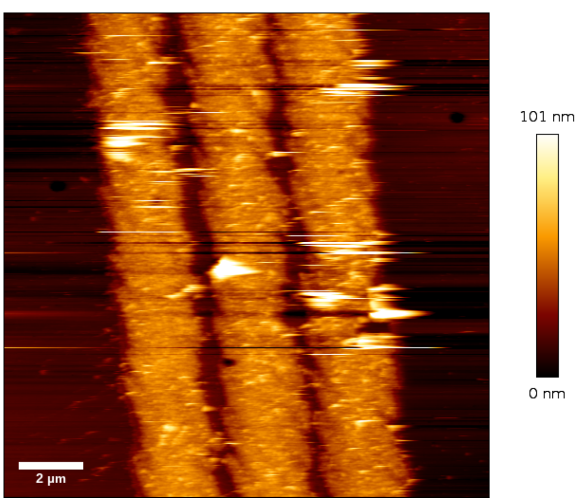
(b) 5 $\mu m\,s^{-1}$



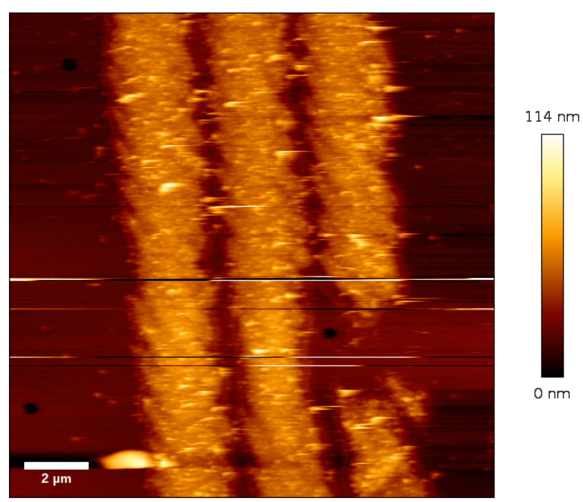
(c) 7 $\mu m\,s^{-1}$



(d) 9 $\mu m\,s^{-1}$

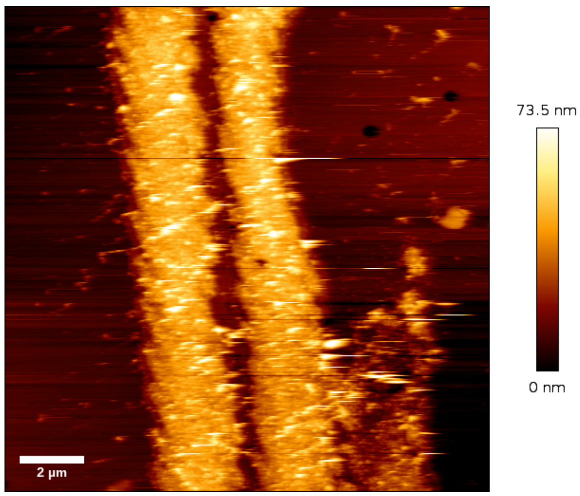


(e) 11 $\mu m\,s^{-1}$

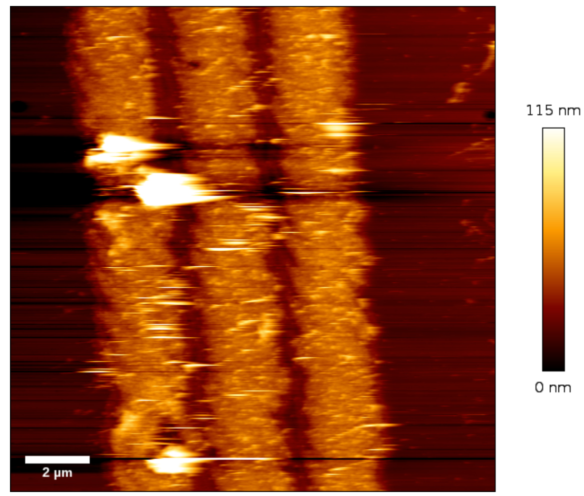


(f) 13 $\mu m\,s^{-1}$

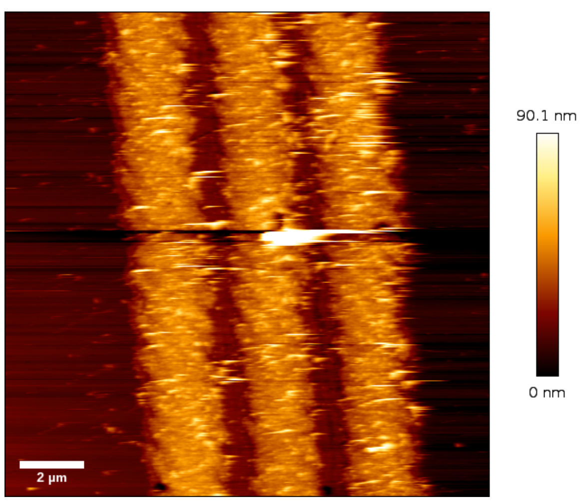
Figure S3: AFM height maps of silver lines written with NA=0.8 objective. Laser wavelength $\lambda = 780\,\mathrm{nm}$, pulse repetition rate 80 MHz, time-averaged laser power $P_0 = 7.4\,\mathrm{mW}$, scanning speeds $v = 3\ldots21\,\mu m\,s^{-1}$



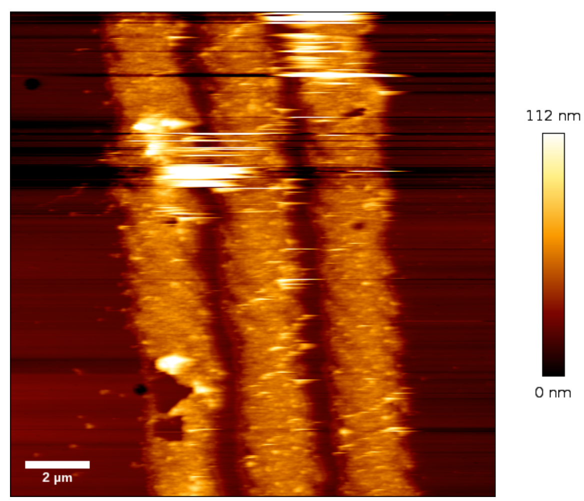
(g) $15\,\mu m\,s^{-1}$



(h) $17\,\mu m\,s^{-1}$

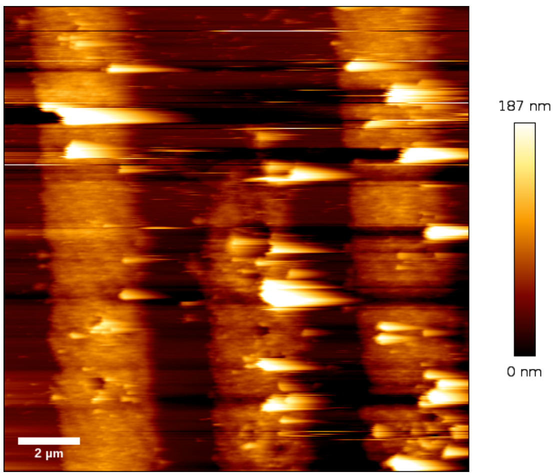


(i) $19\,\mu m\,s^{-1}$

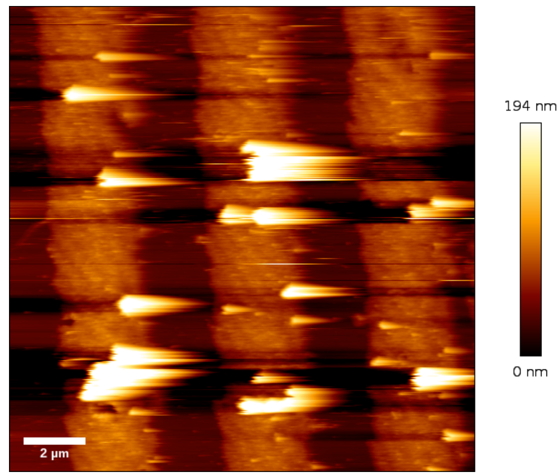


(j) $21\,\mu m\,s^{-1}$

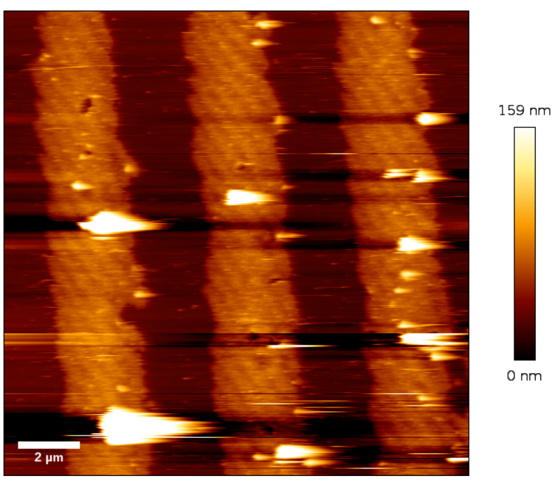
Figure S3: (Continued)AFM height maps of silver lines written with NA=0.8 objective. Laser wavelength $\lambda = 780\,nm$, pulse repetition rate 80 MHz, time-averaged laser power $P_0 = 7.4\,mW$, scanning speeds $v = 3 \ldots 21\,\mu m\,s^{-1}$



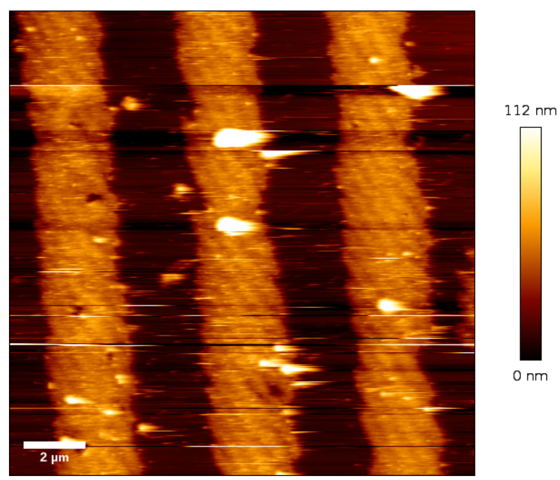
(a) $3\,\mu m\,s^{-1}$



(b) $5\,\mu m\,s^{-1}$

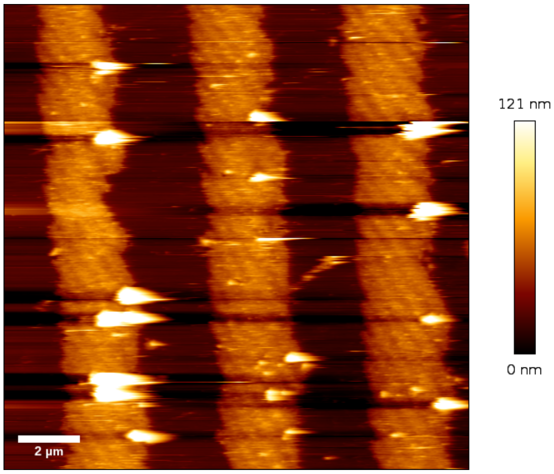


(c) $7\,\mu m\,s^{-1}$

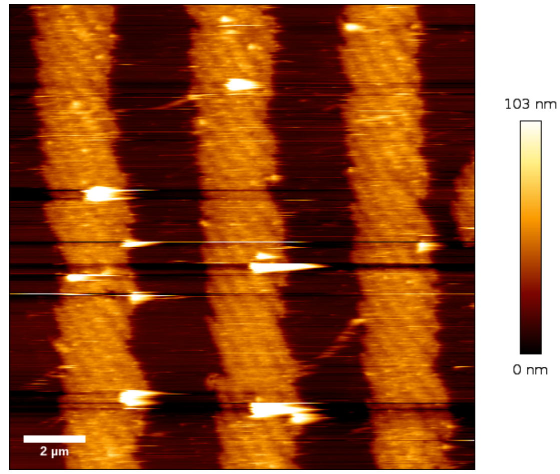


(d) $9\,\mu m\,s^{-1}$

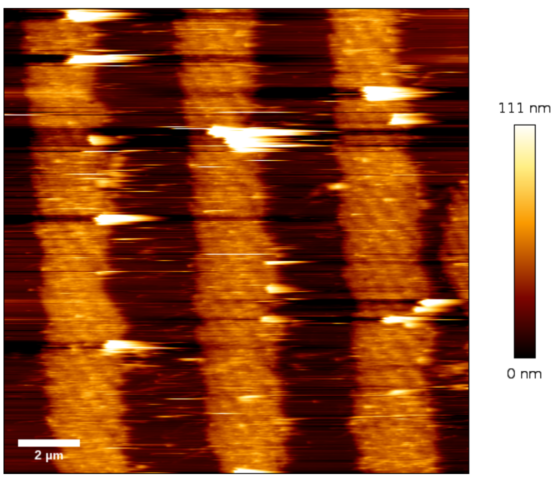
Figure S4: AFM height maps of silver lines written with NA=0.3 objective. Laser wavelength $\lambda = 780\,\mathrm{nm}$, pulse repetition rate 80 MHz, time-averaged laser power $P_0 = 8.6\,\mathrm{mW}$, scanning speeds $v = 3\ldots19\,\mu m\,s^{-1}$



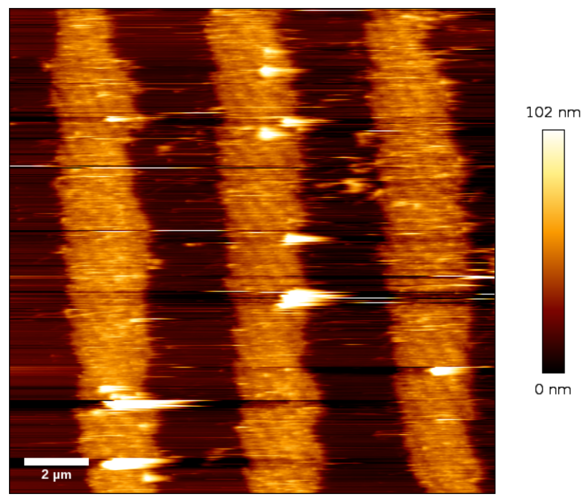
(e) 11 $\mu m\,s^{-1}$



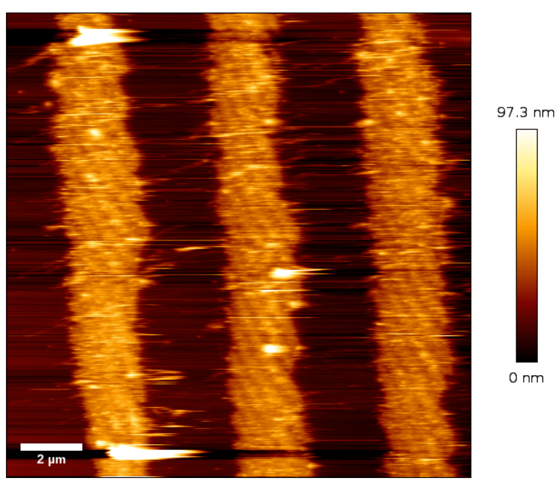
(f) 13 $\mu m\,s^{-1}$



(g) 15 $\mu m\,s^{-1}$



(h) 17 $\mu m\,s^{-1}$



(i) 19 $\mu m\,s^{-1}$

Figure S4: (Continued) AFM height maps of silver lines written with NA=0.3 objective. Laser wavelength $\lambda = 780\,\mathrm{nm}$, pulse repetition rate 80 MHz, time-averaged laser power $P_0 = 8.6\,\mathrm{mW}$, scanning speeds $v = 3 \ldots 19\,\mu\mathrm{m\,s^{-1}}$

2 Dimensions obtained from analysis of AFM images

In order to obtain line width, height, and RMS roughness, the AFM images were processed with a custom Matlab script. Averaging over all lines of a sample, we determined the dimensions of the lines and the standard errors. Artifacts were identified as all values where the AFM indicates maximum height (white spots on images) and removed by the algorithm.

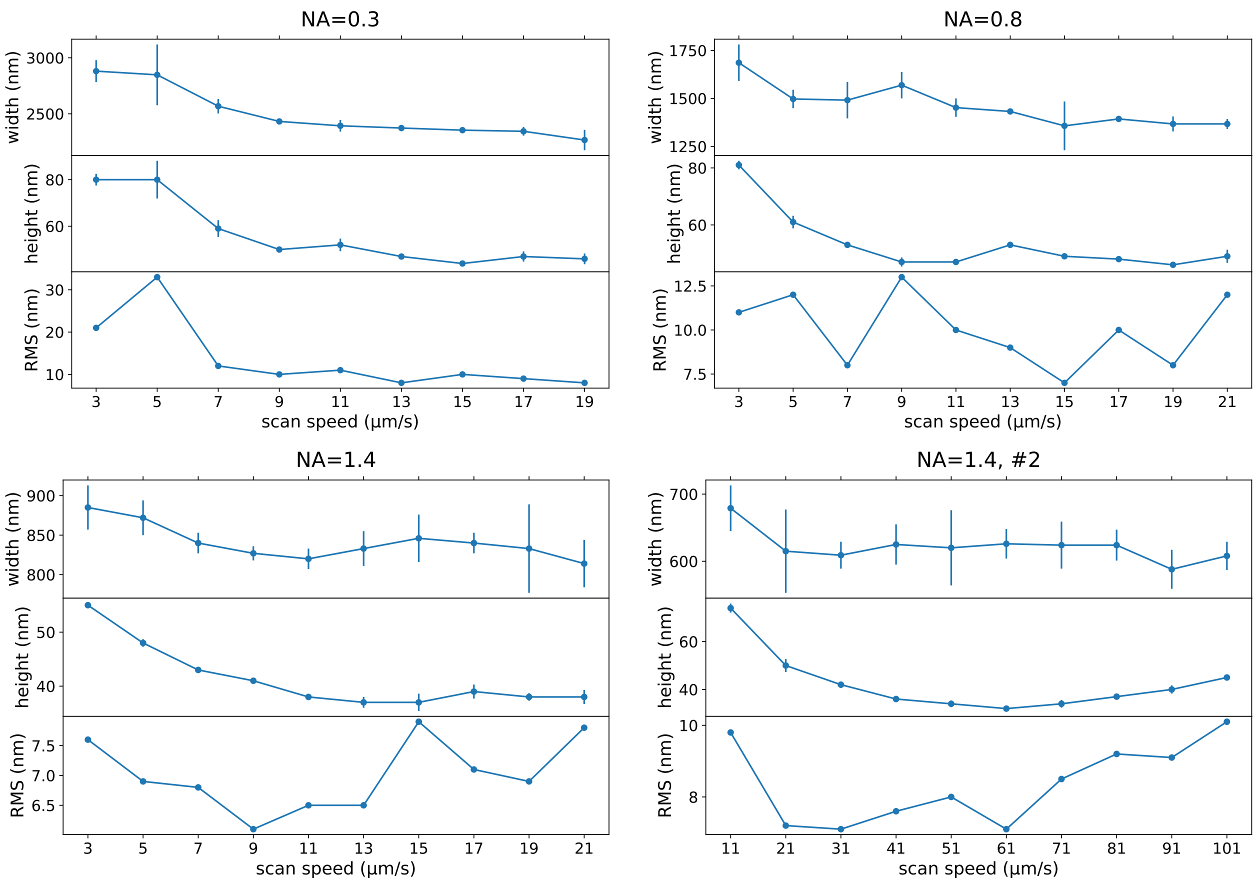


Figure S5: Average line widths and heights as well as RMS roughness obtained from analysis of AFM images for NA=0.3. . . 1.4.

From these dimensions, we calculate the line cross-section as product of average width and height, where the errors are obtained from Gaussian error propagation. Together with the scanning speed, this yields the volumetric silver production rate that serves as input parameter for our simulations.