A Computational Framework for Quantifying Electrical Conductance in Metallic Nanomesh Using Image Processing and Computer Vision Technologies

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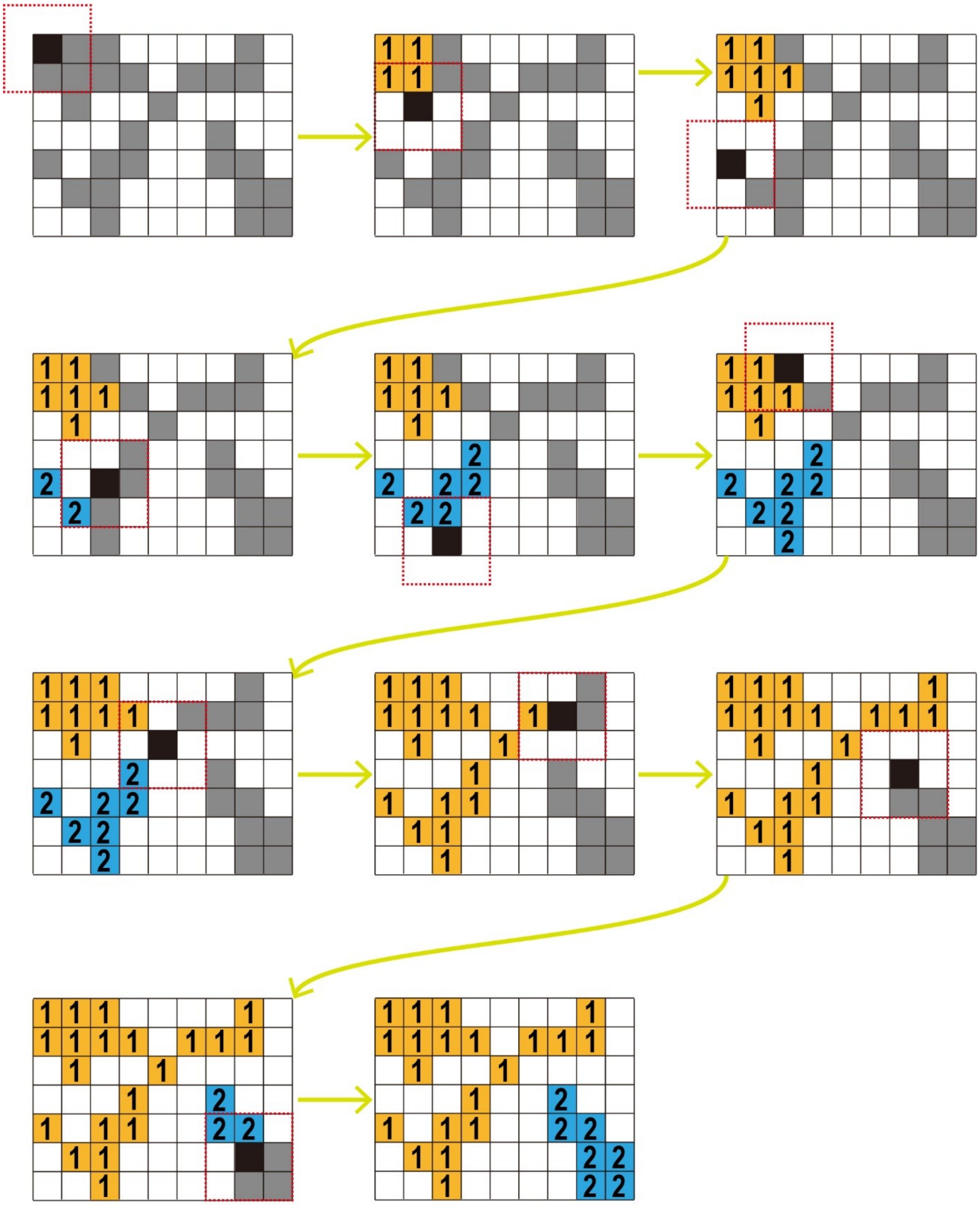


Figure S1. A detailed description of the object pixel clustering process according to their connectivity. A 3x3 filter is indicated by a rectangle with red dash boundaries.

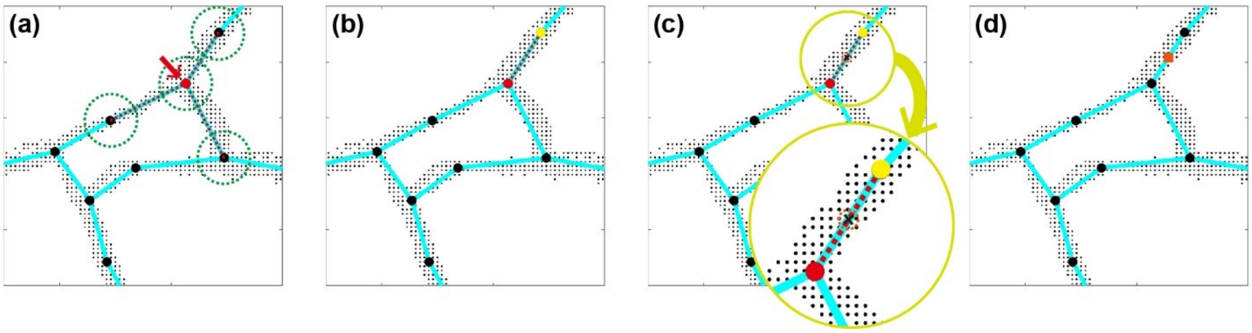


Figure S2. (a) In the initial approach, for any given keypoint with connections at distances over 12 times the inter-pixel distance, (b) the most proximate neighbor is selected for further investigation. (c) Upon identifying the midpoint of the interconnection between the selected keypoint pair, a verification step examines whether object pixels are present within an inter-pixel distance from the midpoint. (d) If this criterion holds, the approach designates the midpoint as an additional keypoint, severs the original linkage between the pair, and establishes new connections from the additional keypoint to each original keypoint. The orange square is the newly identified keypoints.

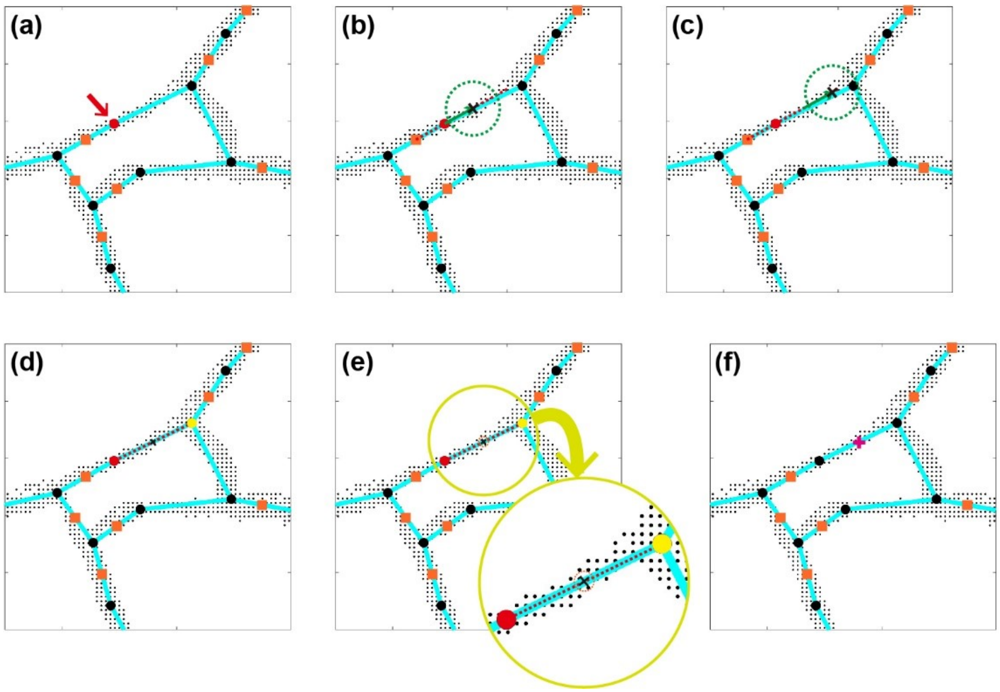


Figure S3. (a) The second approach targets the original keypoints that have acquired a singular new interconnection with the newly introduced keypoint via the first approach. (b) Starting from the selected keypoint, the center of a circular region having a radius of six times the inter-pixel distance traverses in an antiparallel orientation relative to the line segment connecting the designated keypoint and its newly interconnected counterpart. (c) If another original keypoint resides within this circular region before its center reaches a distance 2.5 times the radius, (d) the midpoint between the encountered and the selected keypoints is calculated. (e) In an instance where object pixels exist within an inter-pixel distance from the midpoint, (f) a new keypoint is created at the location, denoted by magenta cross marker. The newly added keypoint establishes interconnections with both original keypoints involved. Existing connections between the two original keypoints, if detected, are subsequently disconnected.

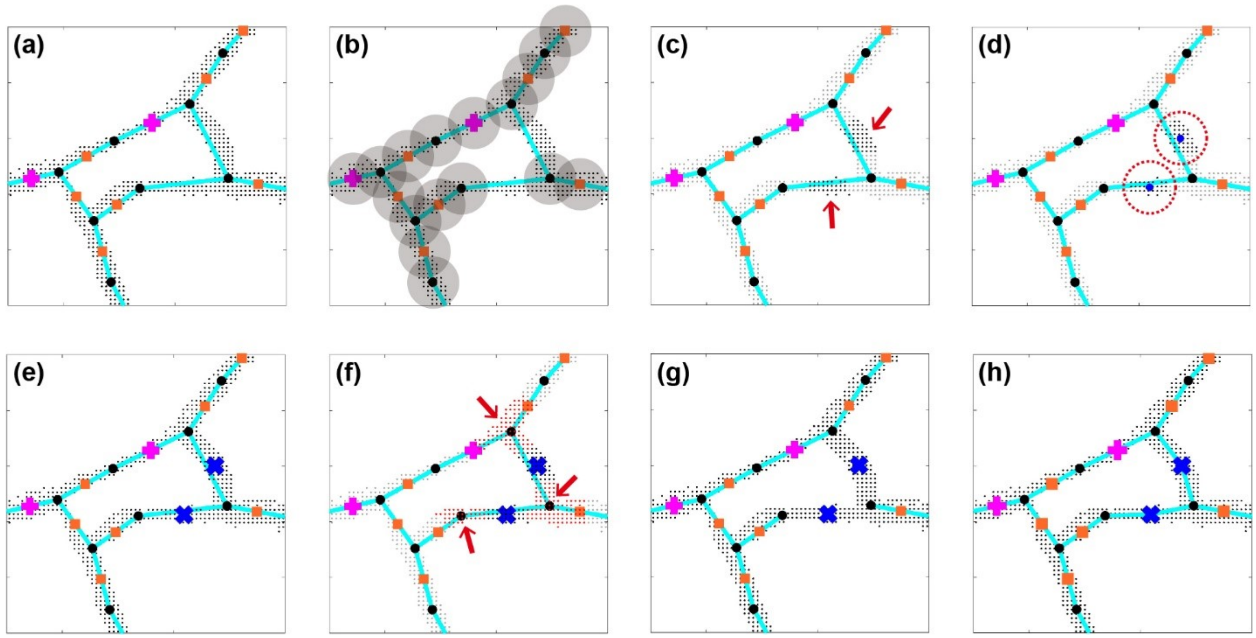


Figure S4. (a, b) In the final approach, object pixels are isolated if the minimum distance between them and any keypoints—including those newly introduced via the prior two approaches—exceeds six times the inter-pixel distance. (c) These selected object pixels are subject to the mean-shift segmentation-based local keypoint detection, as illustrated in Figure 3(a). (d) Upon completion of this procedure, the distances between the newly identified keypoints are assessed. If any distance falls below 12 times the inter-pixel distance, one of the respective keypoints is abandoned to prevent keypoint congestion. (e) The blue x markers represent these new keypoints. (f, g, h) New keypoints form connections with pre-existing keypoints, contingent upon the adjacency of their associated groups of object pixels.

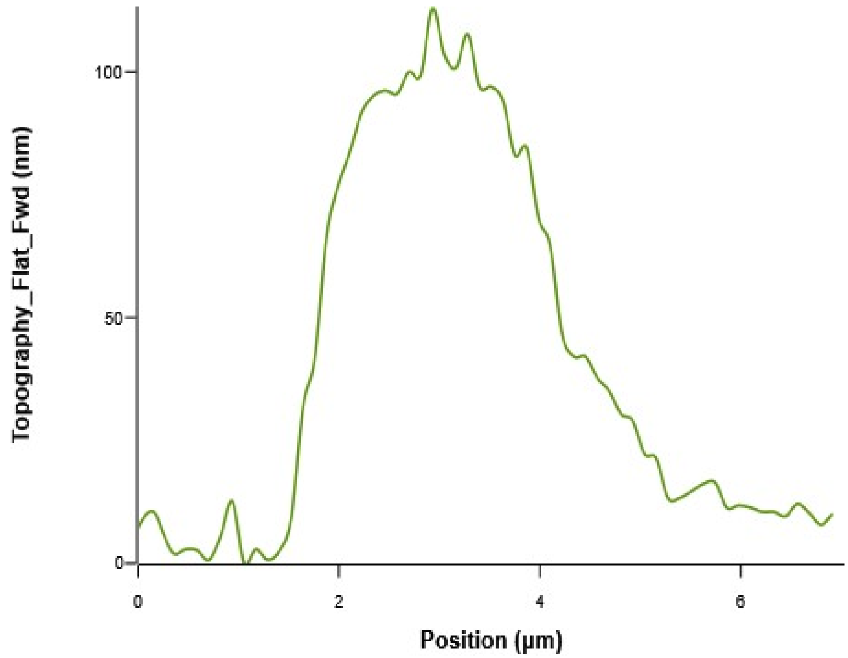
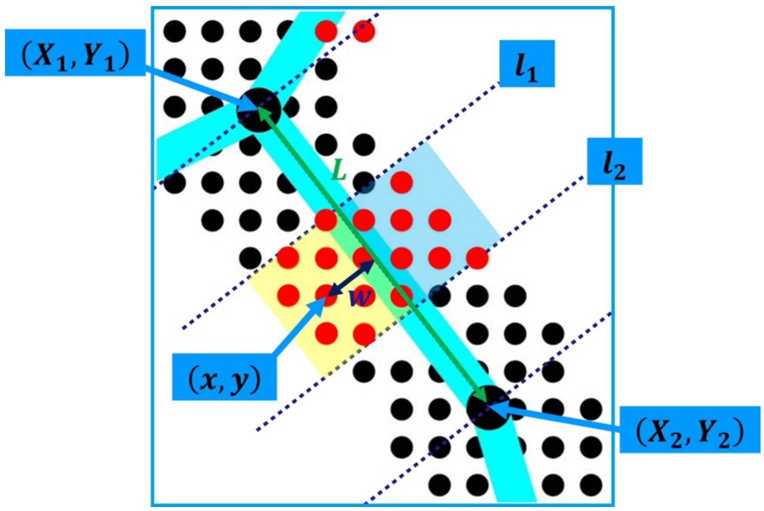


Figure S5. Height profile of the Ag nanomesh as acquired by Atomic Force Microscopy (AFM)

Supporting Information S6



The length, width, and thickness of each constituent line segment are determined to quantify the conductance of the current paths. The length, L, corresponds to the distance between two keypoints that terminate the line segment. This distance is calculated using the following equation:

$$L = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2}$$

where (X_1, Y_1) and (X_2, Y_2) represent the coordinates of these keypoints.

The width is estimated by analyzing the adjacent object pixels located between two perpendicular lines intersecting the line segment at one-third and two-thirds of its length, denoted as l_1 and l_2 in the figure above. The red dots represent these pixels. These pixels are identified by evaluating the values of two equations, A and B

$$A = (X_2 - X_1)x + (Y_2 - Y_1)y + (X_1 - X_2)M_x + (Y_1 - Y_2)M_y$$

$$B = (X_2 - X_1)x + (Y_2 - Y_1)y + (X_1 - X_2)N_x + (Y_1 - Y_2)N_y$$

$$M_x = \frac{2}{3}X_1 + \frac{1}{3}X_2$$

$$M_y = \frac{2}{3}Y_1 + \frac{1}{3}Y_2$$

$$N_x = \frac{1}{3}X_1 + \frac{2}{3}X_2$$

$$N_x = \frac{1}{3}Y_1 + \frac{2}{3}Y_2$$

where (x, y) represents the coordinates of the object pixel under consideration. If the product of these two values is less than zero, $AB < 0$, the corresponding object pixel is included in the width estimation.

The object pixels on either side of the line segment are divided into two subsets based on their spatial orientation relative to the line segment, determined by the following equation:

$$C = (Y_1 - Y_2)x - (X_1 - X_2)y + X_1Y_2 - X_2Y_1$$

If $C < 0$, the object pixel is located in the yellow area, while if $C \geq 0$, it is located in the blue area.

The distance between the object pixel and the line segment, w, is calculated using the following equations.

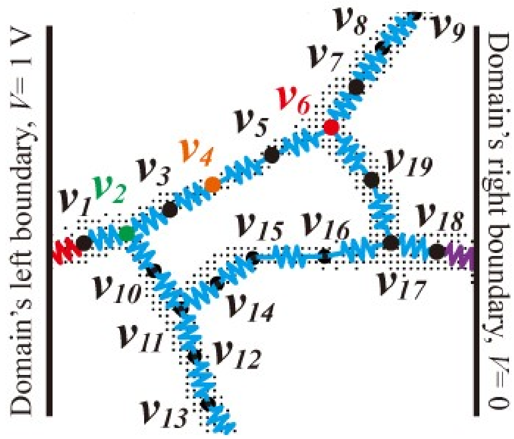
$$a = \frac{Y_1 - Y_2}{X_1 - X_2}$$

$$b = - aX_1 + Y_1$$

$$w = \frac{|ax - y + b\,|}{\sqrt{a^2 + 1}}$$

A statistical assessment calculates the standard deviation of the distances for both subsets, which are multiplied by the exp(1). The sum of these values defines the width of the line segment.

Supporting Information S7



The equations at keypoints designated with voltage variables v_2 and v_4 are as follows:

$$\frac{v_2 - v_1}{R_{2,1}} + \frac{v_2 - v_3}{R_{2,3}} + \frac{v_2 - v_{10}}{R_{2,10}} = 0$$

$$\frac{v_4 - v_3}{R_{4,3}} + \frac{v_4 - v_5}{R_{4,5}} = 0$$

where $R_{i,j}$ represents the resistance of the line segment that connects the keypoints associated with voltage variables of v_i and v_j.

For the keypoint designated with the voltage variable, v_1, which is assumed to be in contact with the left boundary of the simulation domain where a voltage of 1 V is applied, the equation is expressed as follows:

$$\frac{v_1}{R_{1,0}} + \frac{v_1 - v_2}{R_{1,2}} = \frac{1}{R_{1,0}}$$

where $R_{1,0}$ is the resistance of the line segment connecting the keypoint associated with the voltage variable v_1 to the left boundary of the domain, represented by the red resistance symbol in the figure above.

For the keypoint designated with the voltage variable, v_{18}, which is assumed to be in contact with the right boundary of the simulation domain where it is grounded (i.e., $V = 0$), the equation is expressed as follows:

$$\frac{v_{18} - v_{17}}{R_{18,17}} + \frac{v_{18}}{R_{18,\infty}} = 0$$

where $R_{18,\infty}$ represents the resistance of the line segment connecting the keypoint associated with the voltage variable v_{18} to the right boundary of the domain, as indicated by the purple resistance symbol in the figure above.

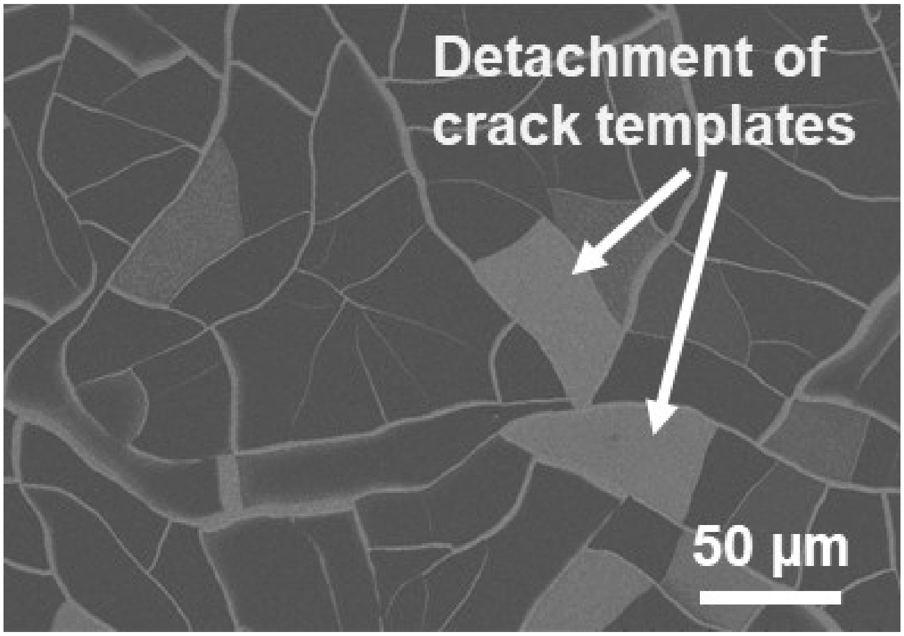


Figure S8. SEM images of Ag nanomesh showing regions where crack templates detached during the drying process. These areas were fully coated with Ag during deposition, leading to the formation of significantly wider current-conducting pathways.

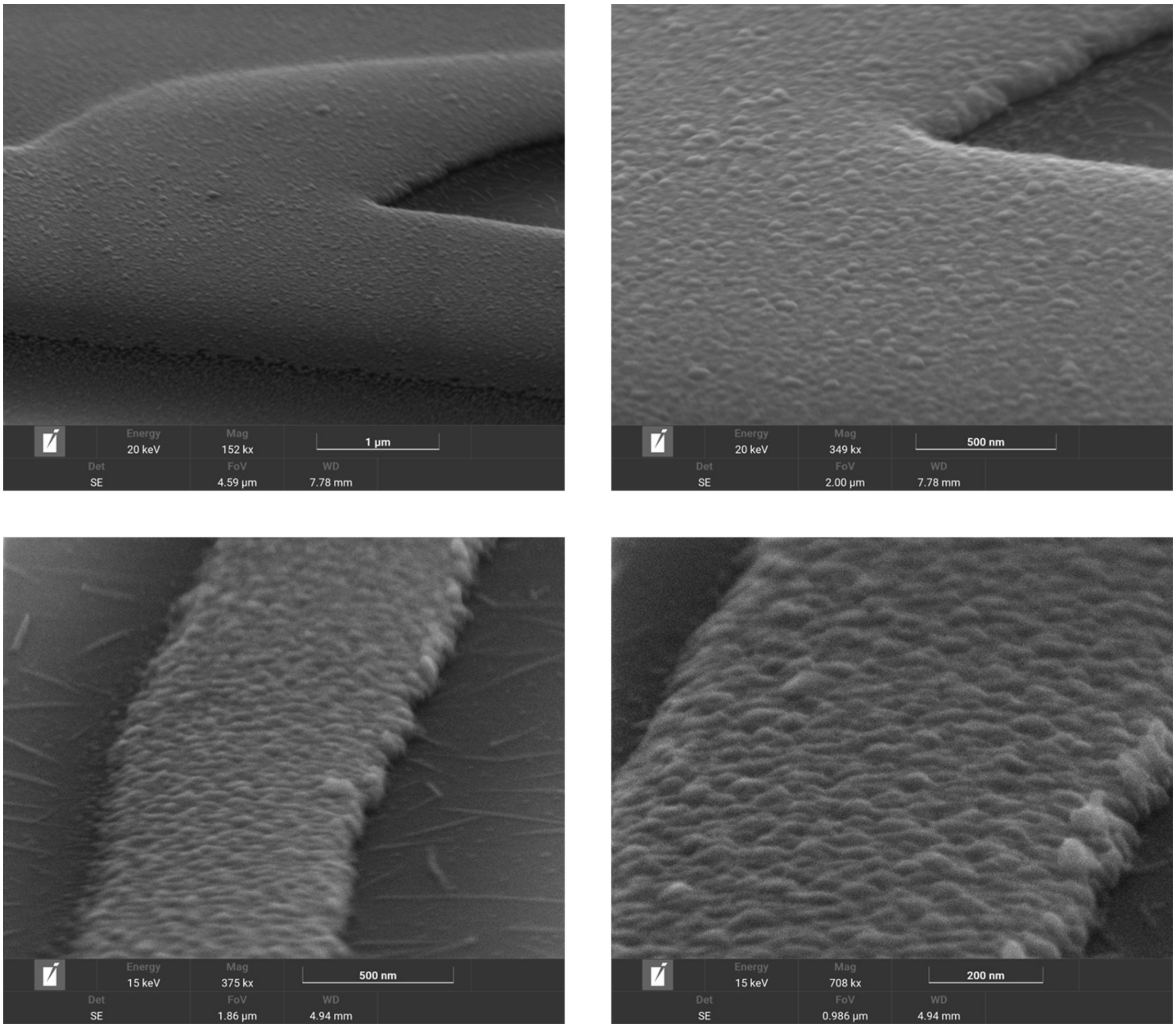
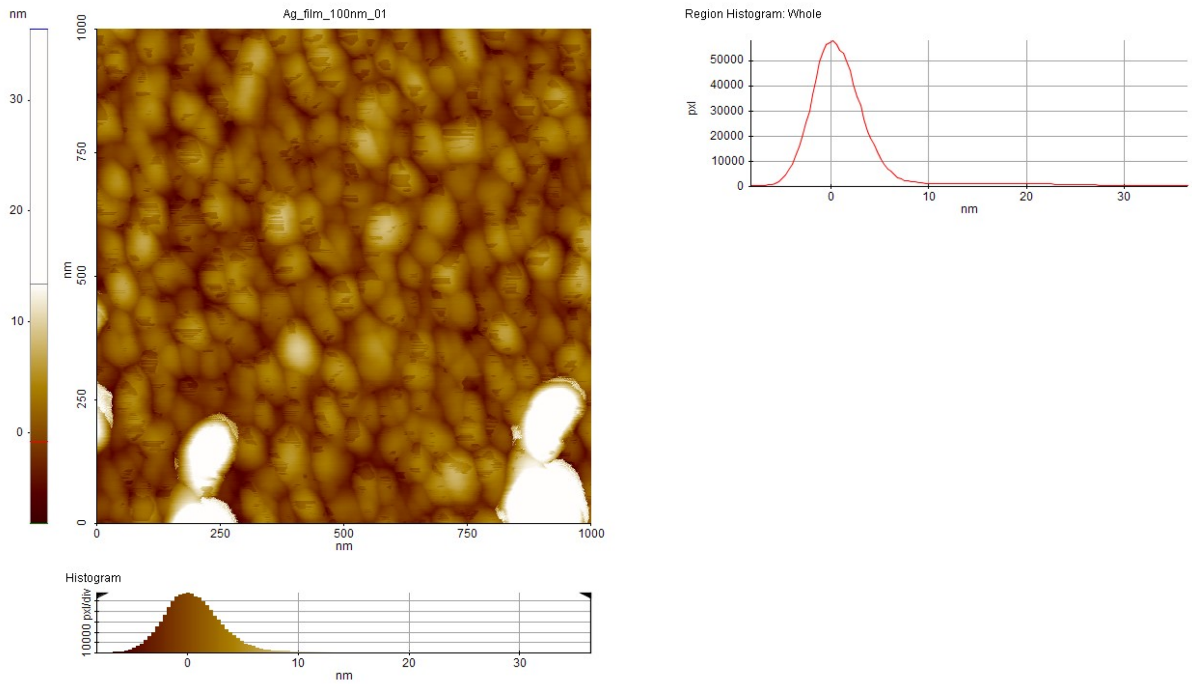


Figure S9. High-resolution FE-SEM images of Ag nanomeshes.



Statistics

Region	Min(nm)	Max(nm)	Mid(nm)	Mean(nm)	Rpv(nm)	Rq(nm)	Ra(nm)	Rz(nm)	Rsk	Rku
Whole	-8.199	36.415	14.108	1.346	44.614	4.924	2.906	44.489	-3.238	17.033

Figure S10. AFM measurement data of Ag nanomesh over 1 μm × 1 μm area.