

Supporting Information

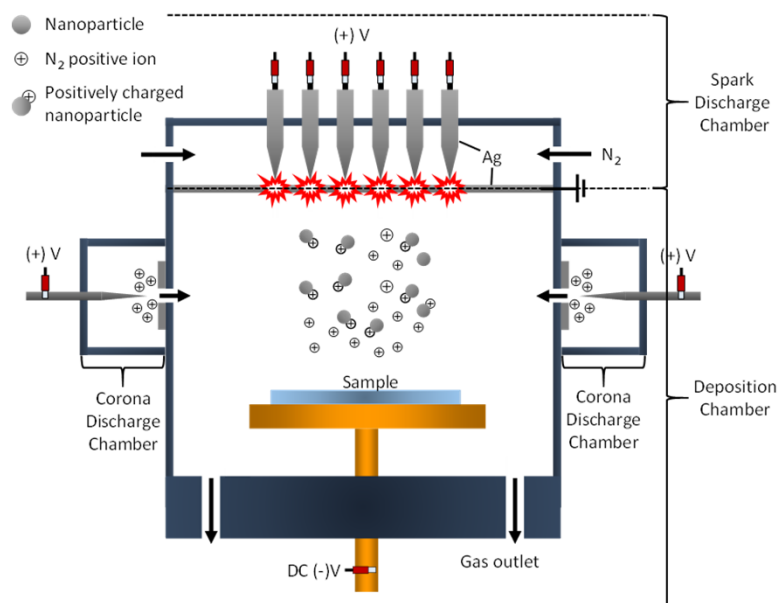


Figure S1: Schematic illustration of the multi-pin spark discharge generator for fabricating 3DM structure arrays over a large area with ensuring uniformity. This multi-pin spark discharge generator consists of three chambers: a pin-to-plate type spark discharge chamber; corona discharge chambers; a deposition chamber.[19]

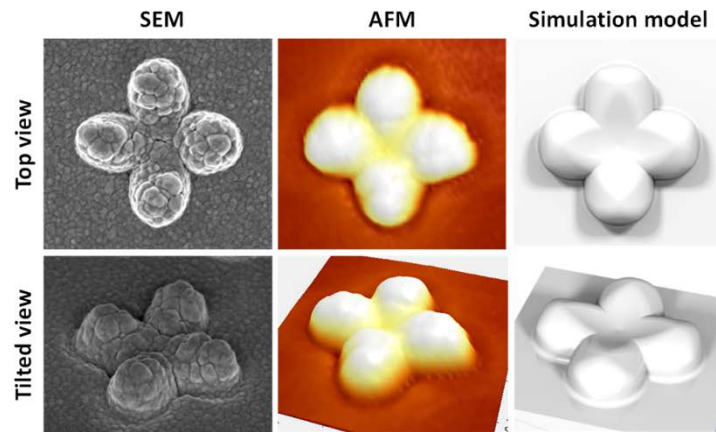


Figure S2: Top and tilted views of the 3DM back reflector measured by SEM (left) and AFM (middle), and those of a simulation model (right) of the 3DM back reflector.

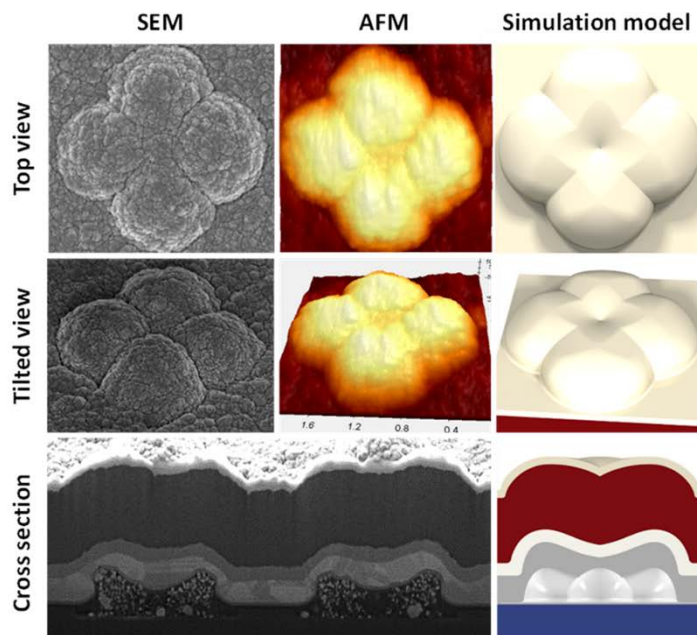


Figure S3: Top, tilted, and cross-sectional views of the 3D solar cell measured by SEM (left) and AFM (middle), and those of a simulation model (right) of the 3D solar cell.

In order to optimize the deposition conditions of Ag back electrodes along the surface morphology of the 3DM structures, 200-nm-thick Ag films were deposited on the same 3DM structure arrays at different vapor incident angles of 0° (normal incident deposition angle), 30° , and 60° . We then compared the three 3D solar cells with different Ag back reflectors to the flat solar cell. The 3D solar cell with the Ag back electrode deposited at the incident angle of 60° shows best performance.

For the case of IAAL, the morphology and the size of 3DM structures are easily adjusted by changing the deposition time as shown in the insets of figure S4(b). To determine the best 3DM structure, we compared the 3D solar cells employing the two 3DM structures covered with Ag back electrodes deposited at the same incident angle of 60° . The 3D solar cell incorporating the 3DM structure arrays deposited for 120 min shows best performance. Figure S4 and table S1 prove the above results.

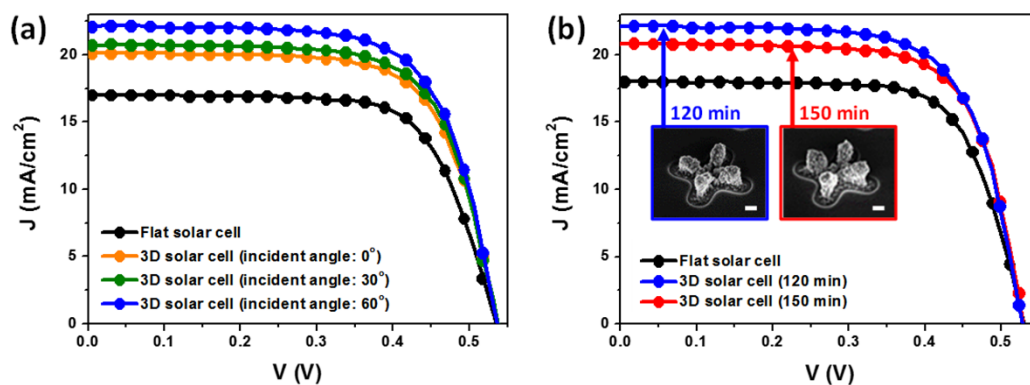


Figure S4: (a) J-V curves of the flat solar cell (black dots) and the 3D solar cells with different Ag back reflectors deposited at the incident angles of 0° (orange dots), 30° (green dots), and 60° (blue dots). (b) J-V curves of the flat solar cell (black dots) and the 3D solar cells with the 3DM structures deposited for 120 min (blue dots) and 150 min (red dots). All scale bars in insets are 200 nm in length.

Table S1: Performance summary of the nc-Si:H thin-film (~500 nm) solar cells in figure S4.

	Deposition time	Incident angle	J_{sc} (mA/cm ²)	V_{oc} (V)	FF (%)	Eff (%)
3D solar cell	120 min	0°	20.1±0.5	0.51±0.01	69.5±0.7	7.2±0.3
		30°	20.7±0.5	0.51±0.01	69.6±0.7	7.4±0.3
	150 min	60°	22.1±0.6	0.51±0.01	68.7±0.7	7.8±0.3
			20.8±0.5	0.50±0.01	70.5±0.7	7.3±0.3
Flat solar cell			17.1±0.4	0.53±0.01	70.9±0.7	6.4±0.2

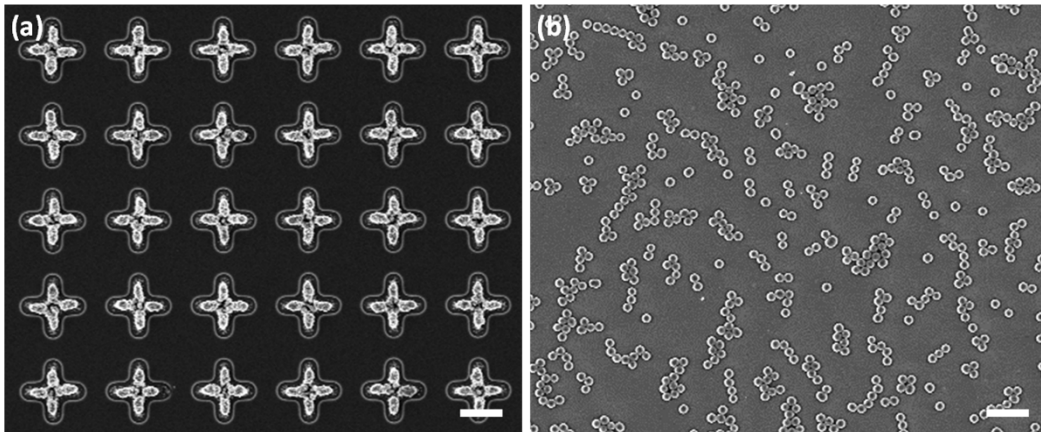


Figure S5: SEM images show top views of (a) the 3DM structures and (b) the NPCs with the same percentage of the surface coverage. The scale bars are 1 μm in length.

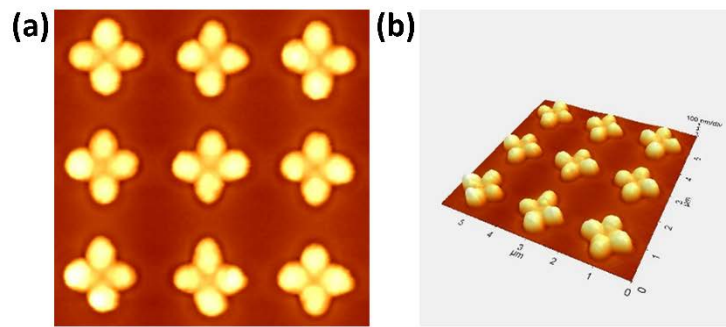


Figure S6: (a) Top and (b) tilted views of the AFM image of the 3DM back reflector.

Table S2: Analysis of the increased surface area resulting from the 3DM back reflector in figure S6.

Surface area [μm^2]		Rate of increase [%]
Flat structures	3DM structures	
36	43.7	21.4