Supporting Information

A dual-scale metal nanowire network transparent conductor for highly efficient and flexible organic light emitting diodes

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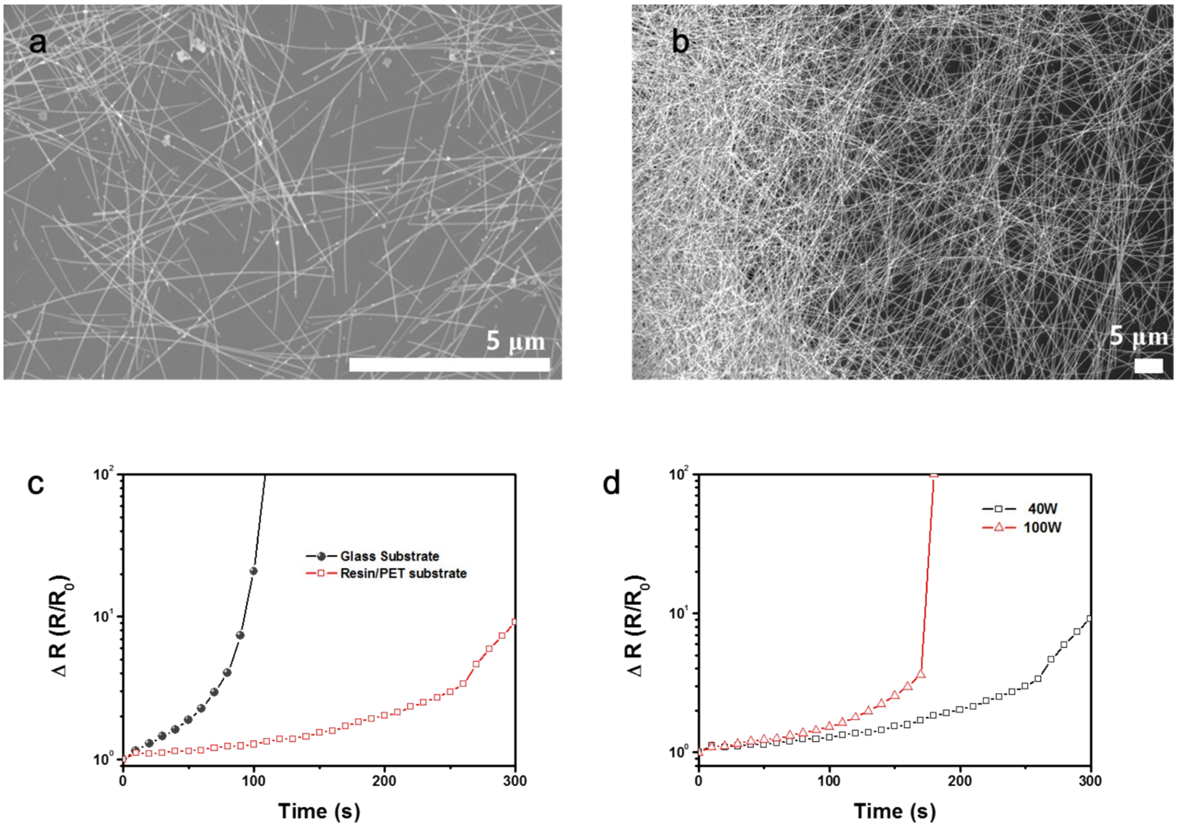

Figure S1 SEM pictures of synthesized (a) short/thin AgNWs (10 μm / 40 nm) and (b) long/thick AgNWs (100 μm / 100 nm). c) UV resistant test of embedded NWs versus NWs on a bare glass substrate under 40 W plasma treatment. d) UV failure test of embedded NWs under 40 and 100 W plasma power treatment condition.

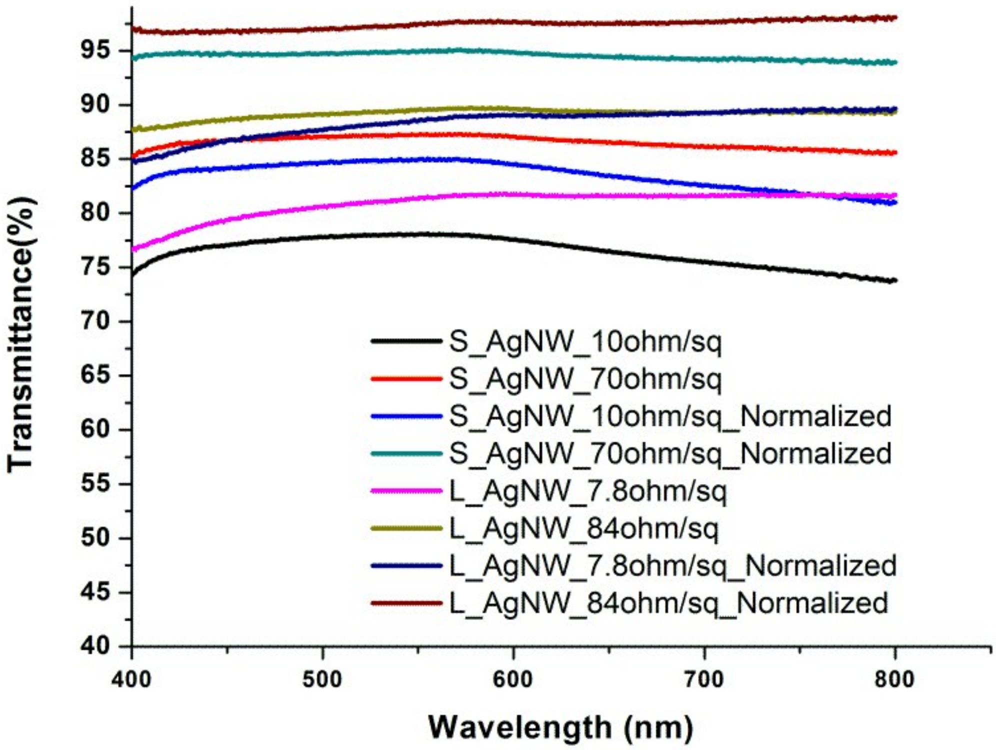

Figure S2 Spectral transmittance of various transparent electrode based on different AgNWs structures.

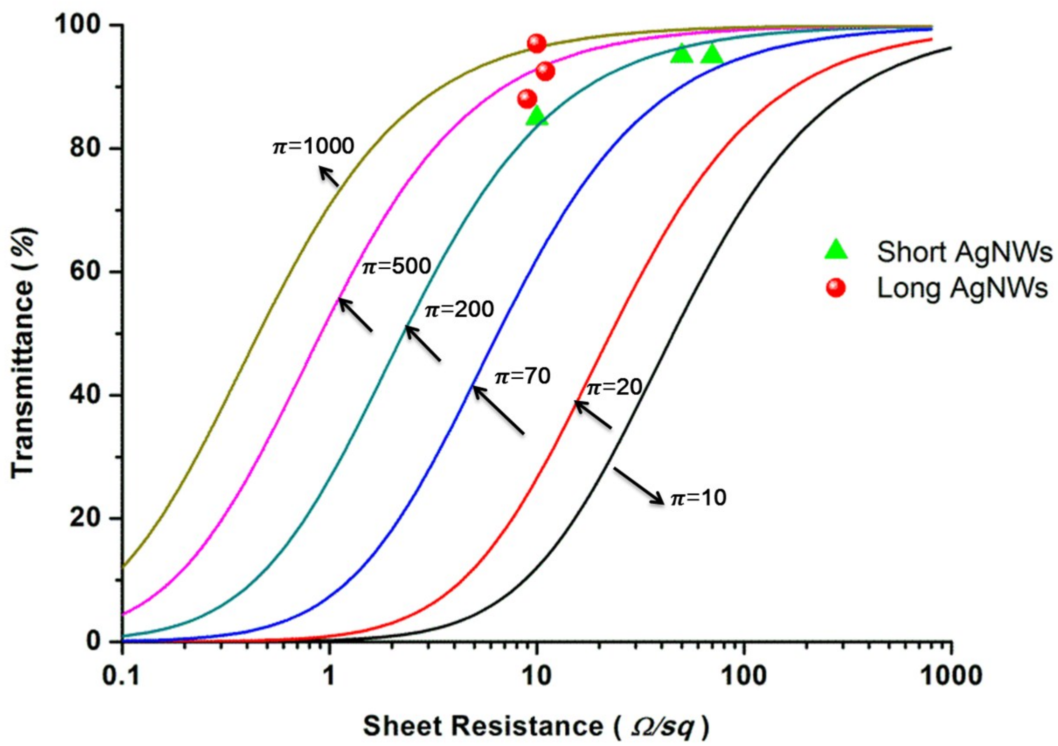

Figure S3 Plotted figure of merit based on calculation (eq.1) and FOMs of fabricated electrodes

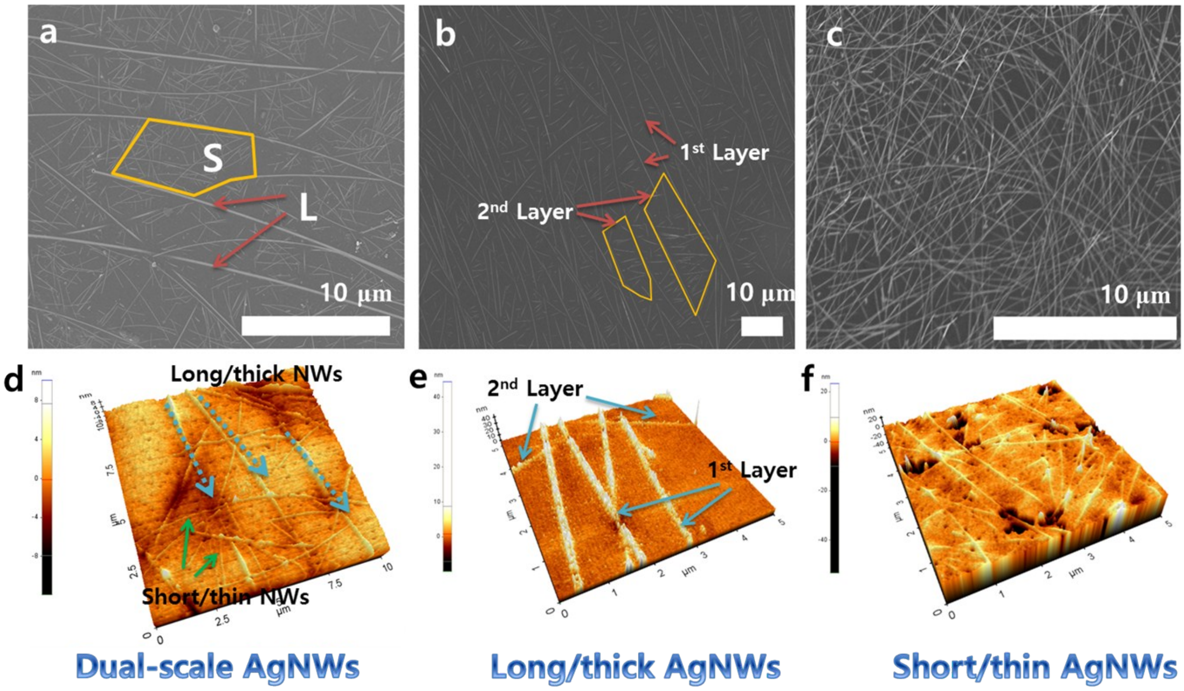

Figure S4 SEM and AFM analyses of fabricated transparent conductor using (a, d) dual-scale AgNW percolation network, (b,e) only long/think AgNW percolation network, and (c,f) only short/thin AgNWs percolation network.

As shown in **Figure S2(b)**, NWs included in 2nd layer seems like dashed lines by covering of the polymer matrix. Moreover, 3rd or upper layers are perfectly impregnated and it disturbs path of electrons vertically. Many segments of short/thin AgNWs shown in the SEM image (**Figure S2(c)**) are impregnated in the polymer, as confirmed by the AFM image (**Figure S2(c)**), leading to the decrease in effective electrical area.

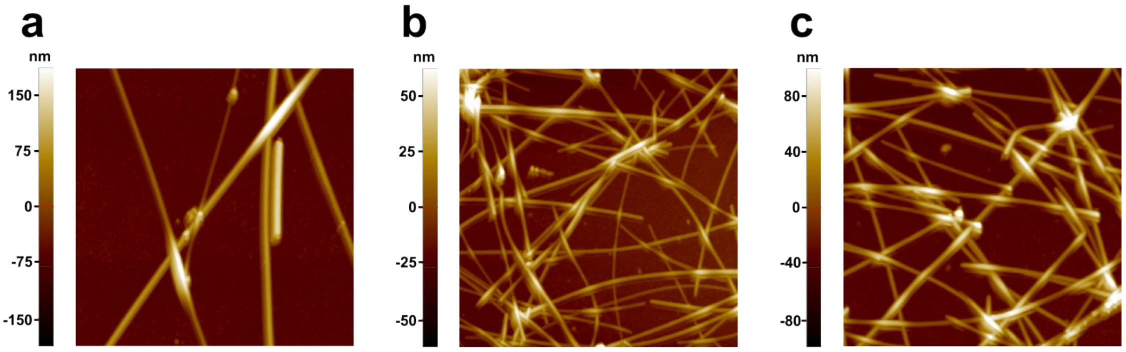

Figure S5. AFM topography information of AgNWs network before embedding (a) long/thick AgNWs (b) short/thin AgNWs (c) dual-scale AgNWs.

	Long/thick AgNWs	Short/thin AgNWs	Dual-scale AgNWs

Before embedding (nm)	32.36	26.27	28.09
After embedding (nm)	1.607	3.237	1.845

Surface Roughness

We performed AFM analysis for AgNWs deposited onto glass substrate which is prior state to embedding process. Fig S3 shows difference in coverage according to types of AgNWs. RMS values of the long, short and dual AgNWs are 32.36nm, 26.27nm and 28.09nm respectively. RMS value of embedded electrode is calculated from Fig 4.(d-f) in main manuscript. RMS values decreased conspicuously through burying of AgNWs. Interestingly, RMS of short AgNWs is lowest among the electrode before embedding process but RMS of long and dual AgNWs is approximately twice smaller than that of short AgNWs after embedding process. While long AgNWs are buried in UV resin well, short AgNWs are too thin to be held. Long AgNWs can also hold short AgNWs not to be detached from surface in dual AgNWs network.

Surface Coverage

In previous study, coverage regarding 1-dimensional network film has been reported by Wiley Group [1]. In this report, coverage Ac was calculated by following equation.

$$\%T=100-87Ac \quad \text{(eq. 1)}$$

This equation is related to transmittance of fabricated electrodes without diameter of nanostructures. Based on this equation, calculated coverage are 0.057, 0.086 and 0.0919 for each long / short / and dual scale case respectively. Higher value means larger coverage. Calculated areas of voids in percolation network are ~7μm2, ~1μm2 and ~5μm2 for each long/short/ and dual scale. It clearly means that adding short/thin AgNWs into larger network can reduce the size of voids and increase the coverage. However, although percolation network consisting of short/thin AgNWs has smaller voids compared to others, its increased number of junctions disturbs the current spreading and makes surface rough in the electrode. Thus, dual-scale NWs network is employed to minimize shorts and to provide moderate coverage. In addition, its coverage also has been measured by image analysis tool. As shown in figure S6, SEM images are transferred to black-and-white images by segmentation in Image Pro and counted based on pixels. Although coverages are different, each sample has same sheet resistance (50ohm/sq). Surface coverage (L1:S1 ratio) is increased in dual scale compared to electrode based on long AgNWs and quantified in table S1.

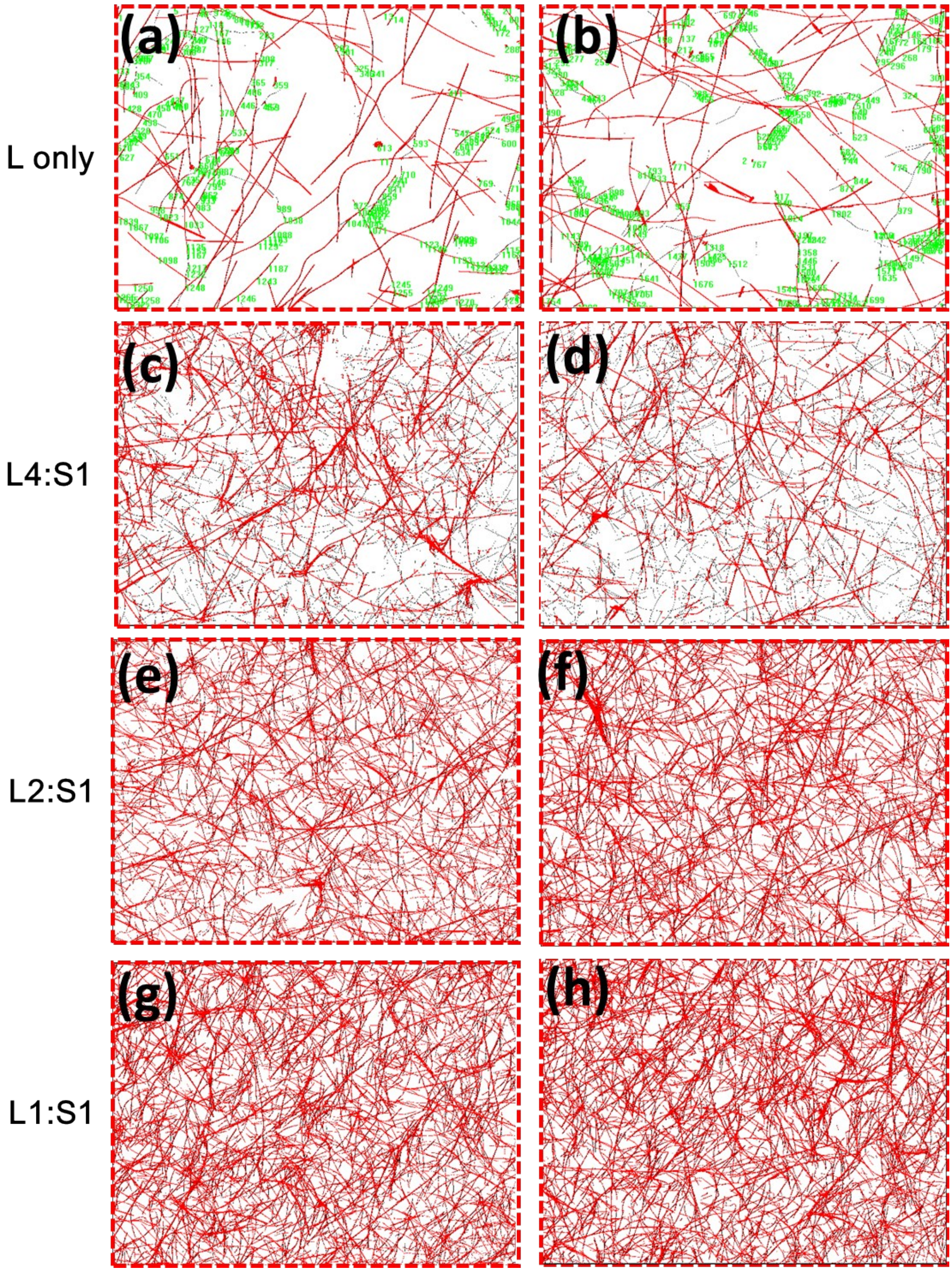

Figure S6. Transformed and counted SEM images based on different coating ratio by segmentation in Image Pro.

Table S1. Counted each area (A.U.) in transformed SEM images.

	Sum of Dark Area (A.U.)	Sum of White Area (A.U.)	Covered Area (%)
a (L)	*49246*	*1171954*	*4.0325*
b(L)	*58378*	*1160610*	*4.789*
c(L4:S1)	*125927*	*1057978*	*10.6365*
d(L4:S1)	*97613*	*1080837*	*8.2831*
e(L2:S1)	*165348*	*1050492*	*13.5299*
f(L2:S1)	*212752*	*1003008*	*17.4995*
g(L1:S1)	*233787*	*983173*	*19.2107*
h(L1:S1)	*257442*	*954691*	*21.2387*

Coating Ratio and its Performance on OLED

The ratio of long/short nanowires could be easily controlled by mixing each type of as-cleaned nanowires in solvents in desired ratio. In addition, Phosphorescent green flexible OLEDs are fabricated on transferred electrode of different ratio of AgNWs. 1:1 and 1:2 ratio of long nanowires and short nanowires are compared with normalized efficiency. Performance of the OLEDs is changed by mixing ratio and it was optimized to 1:1 ratio. As shown in figure S7, 1:1 mixing ratio of fabricated OLED has higher efficiency that 1:2 mixing ration of that in every region of current density. Therefore, we chose 1:1 ratio of the nanowires as optimal condition for fabricated device.

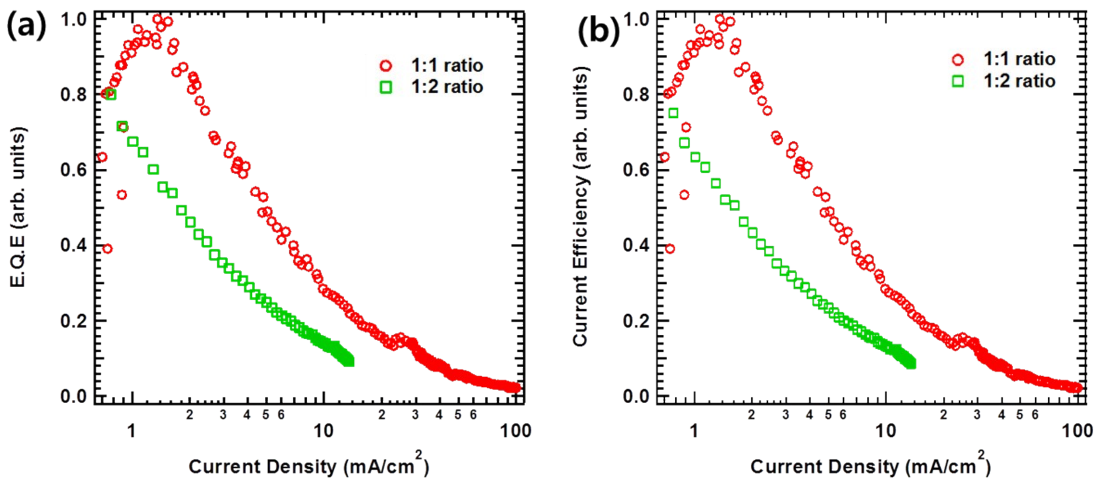

Figure S7. OLED characterization in (a) E.Q.E. and (b) current efficiency based on different AgNWs ratio.

[1] S. Bergin, Y. Chen, A. Rathmell, P. Charbonneau, Z. Li, B. J. Wiley, Nanoscale, 2012,4, 1996.