Quantitative analysis for properties of transparent conductive film

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In recent years, flexible transparent conductive film (TCF) recently gained significant attentions, because it is an important part of next-generation flexible electronics. Especially, metal nanowires with high aspect ratio has come under the spotlight due to not only forming a thin layer by conventional liquid coating process but also superior opto-electric properties, especially in terms of transmittance and sheet resistance. It should be noted that the performance of these films usually depends on the nano/micro percolation network structures in the TCF. With a proper magnification, they can be visualized via electron microscopy such as scanning electron microscopy (SEM). Such images contains valuable information about the structures, and they can be extracted via properly designed image analysis.

Note that there are lots of methods to fabricate TCF such as vacuum filteration, contact printing *etc*. However those methods are not suitable for mass production, therefore it is advisable to use a solution process, e.g. liquid coating method such as slot coating, blade coating, or dip coating *etc*. Furthermore, since metal nanowires can be dispersed in many solvents without difficulty, liquid coating is more fascinated. In this study, we focused on silver nanowires TCF fabricated by simple dip coating method. In dip coating, a wet film thickness is determined by force balance of capillary force, viscous force and gravitational force. Here, lots of factors can affect to the force balance, e.g. substrate drag velocity and solvent physical properties can affect to capillary force so that it affects wet film thickness [1]. Meanwhile, solvent volatility is related to evaporation rate so that it can affect to alignment of wires [2]. Therefore under various experiment condition, opto-electric properties of

TCF is also varied. To achieve TCF that has low cost yet high performance in mass production, evaluation of opto-electric properties can be crucial to identify which processing condition is optimum. Herein, we propose a systematic approach for analyzing metal nanowire network inside the TCF. This approach can draw important microscopic information and it is eventually used to determine the desirable processing conditions and improve the designs of fabrication device, thus fulfilling the ultimate goal of materials processing: utilizing macroscopic processing methods to control the features of microscopic or even submicroscopic material. The approach is summarized as following paragraph.

The first step is to segment the nanowires from image by separating it from backgrounds to identify where the wires are placed. [3]. Two types of analyses are followed: 1) Fourier analysis and 2) matrix manipulations of Kirchhoff law. In Fourier analysis we used specialized proposed filter, namely Gaussian/notch pass filter, for extracting each of wires [4]. Then, general properties of networks such as alignment distribution, length distribution, number of wires, and area fraction can be measured: they can be used to evaluate the effect of coating methods and transmittances. Figure 1 shows the resultant analysis. The Kirchhoff law-based analysis on the percolation network can be used to estimate electrical performance of networks. Here, the network can be represented as an incidence matrix using graph theory. Then Kirchhoff equation is formulated from the matrix, and the conductivity analysis on the network can be done for evaluating the performance of TCF. Figure 2 shows the resultant analysis.

[Reference]

[1] Ahn G., Kim D., Kim O., Nam J., "Analysis of transparent conductive silver nanowire films from dip coating flow", J. Coat. Technol. Res, **12** (5), p. 855–862, (2015)

[2] Jang H., Kim D., Tak H., Nam J., Kim T., "Ultra-mechanically stable and transparent conductive electrodes using transferred grid of Ag nanowires on flexible substrate", Current Applied Physics, **16,** p. 24-30, (2016)

[3] Kim D., Choi J., Nam J., "Entropy-assisted image segmentation for nano- and micro-size networks", *Journal of microscopy,* **262** (3), p. 274–294, (2016)**.**

[4] Kim D., Choi J., Nam J., "Image analysis for measuring rod network properties", *Measurements science and technology,* ***26***, p.125601 (2015).

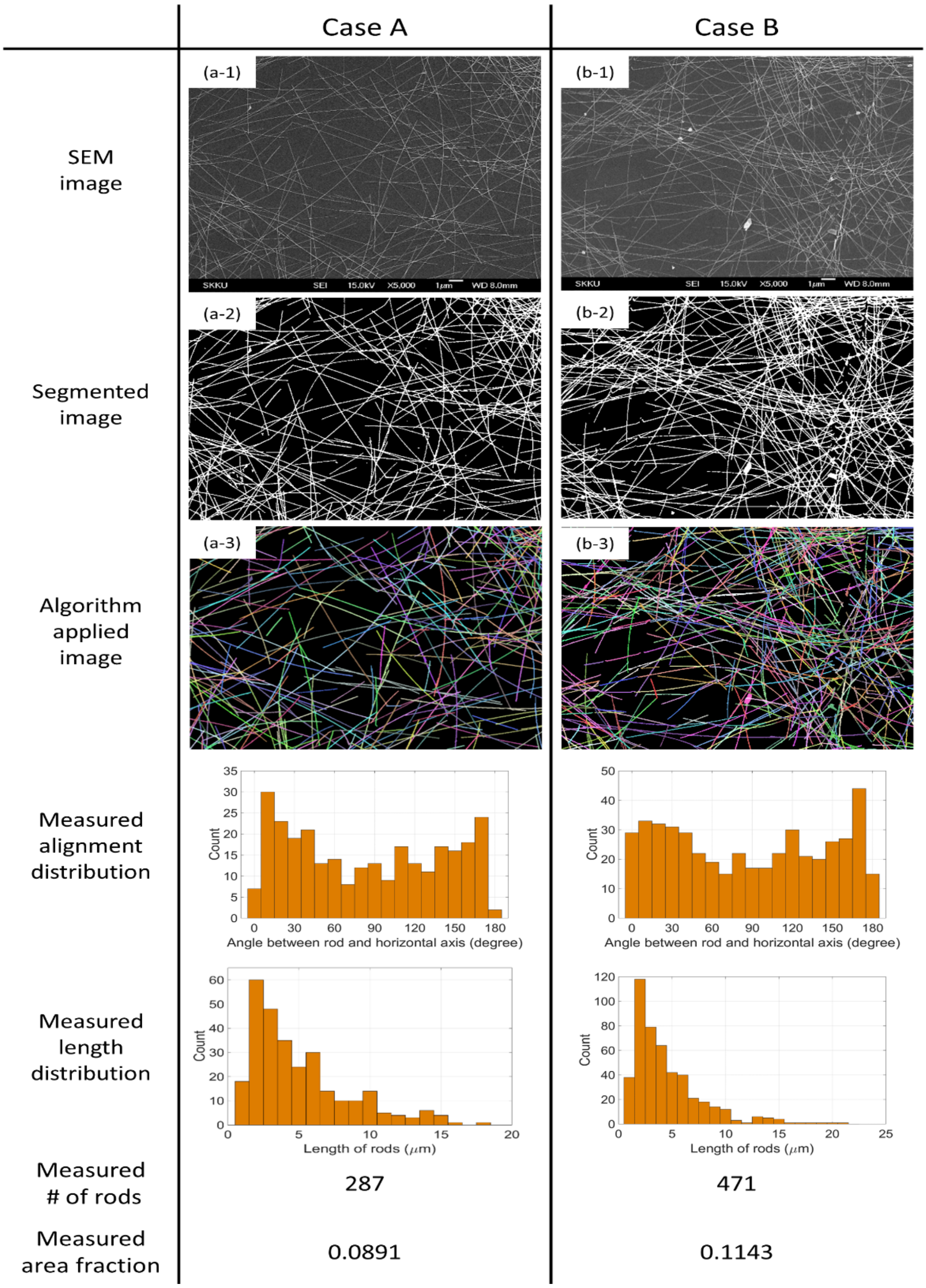
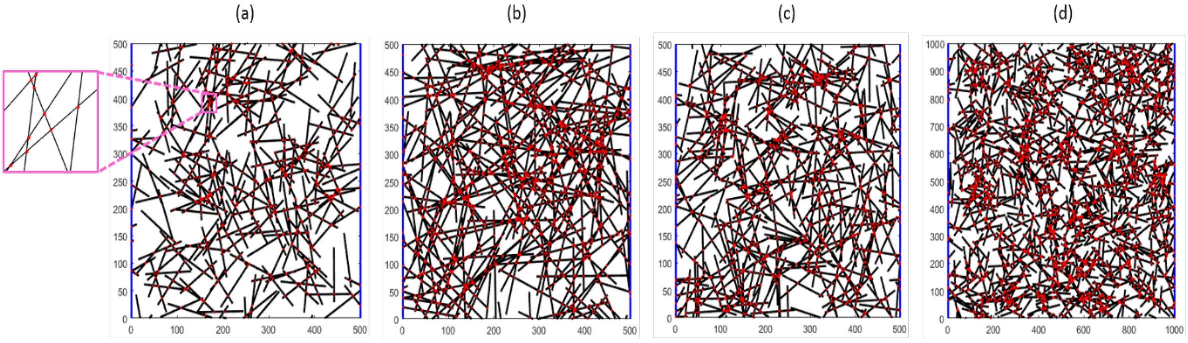


Figure 1 Application of algorithm to the electron microscope images (900×1280 pixels) of the silver nanowire transparent conductive film fabricated by dip coating by the substrate withdrawal speed $V_s = 600\ \mu\mathrm{m/s}$ (case A) and $V_s = 800\ \mathrm{\mu m/s}$ (case B). Images in the second row shows the results from image segmentations used the method proposed by Kim *et al.* [3]. The detected nanowires are displayed in the images of the third row. The measured properties such as alignment distribution, length distribution, total number of rods, and area fraction are shown in the fourth, fifth, sixth, and seventh rows, respectively.



Parameters				
l [a.u.]	100	200	100	100
n [#/a.u.^{2}]	0.001	0.001	0.0015	0.001
L [a.u.]	500	500	500	1000
Results				
$i_{\rm in}^{\rm P}, i_{\rm out}^{\rm P}$ [A]	0.0453, -0.0453	1.5285, -1.5285	0.1795, -0.1795	0.0469, -0.0469
R_s [Ω]	2.209×10^3	6.542×10	5.573×10^2	2.131×10^3
Computation time [s]	0.0914	0.358	0.315	1.294

Figure 2 Sheet resistance analysis to the synthetic nanowires random networks. Here, parameter $l, n,$ and L denote length of wires, number density of wires on the given system, and system size, respectively. The results symbols $i_{in}^{\rm p}$, $i_{out}^{\rm p}$ and R_s denote analyzed input current, output current and estimated sheet resistance, respectively. Here, each of contact resistance is assumed to be 2000Ω and applied voltage is 100V.