Computational Study of Random Nanowire Networks: Optimization of Conductivity through Orientation

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Abstract

Transparent conductors are ubiquitous in modern electronic devices. The majority of devices use Indium Tin Oxide (ITO) for this purpose. ITO, however, is plagued by issues including material scarcity, high manufacturing costs, and brittleness. Random metal nanowire films show potential as transparent conductors, but their performance must be improved before large-scale displacement of ITO can occur. In this study, nanowire orientation was investigated as a method for optimizing performance of random metal nanowire films. A computational model was developed to generate random nanowire networks and calculate their electrical conductivity. The model was then used to investigate the effects of nanowire orientation on network conductivity using three different distributions: normal, uniform, and discrete bimodal. For all three, conductivity is maximized for an optimal degree of restriction, corresponding to standard deviations of 35°, 33°, and 30°, respectively. For the first two distributions, conductivity increases with respect to the isotropic control by 20% and 25%, respectively. Surprisingly, the bimodal distribution showed no such enhancement, emphasizing the crucial role of randomness in orientation effects. These results are expected to support wider adoption of metal nanowire networks as transparent conductors, which will reduce costs and accelerate development of electronic devices.

1. Introduction

Many modern technologies such as touch screens, solar cells, and LCD displays require transparent conductors, which are materials that conduct electricity without blocking light [1-6]. Touch screens, for example, need to detect electrical charges to pinpoint a location without blocking the display. Transparent conductors are characteristically difficult to find or create because in nearly all solids, transparency and conductivity have a negative correlation. Indium Tin Oxide (ITO), which has an excellent combination of conductivity and transparency, currently dominates the market for transparent conductors [7]. ITO, however, is plagued by a multitude of issues of its own. High demand and scarcity of Indium make the material very expensive. Furthermore, manufacturing processes to deposit ITO are often difficult, and the material is brittle, making it unsuitable for modern flexible electronics being developed for various applications [1-3, 7]. As a result of these issues, a suitable replacement for ITO has the potential to significantly reduce costs of many current technologies, as well as accelerate development of new electronics.

Several alternatives to ITO have been investigated in recent years. These include graphene films, carbon nanotube dispersions, as well as ordered and random metal nanostructures [3]. Figure 1 shows a few examples of these alternatives. In particular, random networks of metal nanowires have shown high potential to match ITO in both transparency and conductivity. Random metal nanowire films are made by depositing nanowires from a suspension uniformly onto a substrate such as polyethylene terephthalate or glass. The resulting films are composed of randomly placed, low resistance, nanowires that leave a large proportion of the surface area uncovered, thus allowing both high transparency and conductivity. In addition to these characteristics, the films also display superior flexibility to ITO and are compatible with simpler and more scalable manufacturing processes [3-4, 7]. Networks made of silver nanowires have already entered the transparent conductor market in their first forms [8]. This technology, however, still does not match the performance of ITO; in order to foster wider adoption and displacement of ITO, improvements to the performance of the material must be made. Specifically, one wishes to improve conductivity without sacrificing transparency.

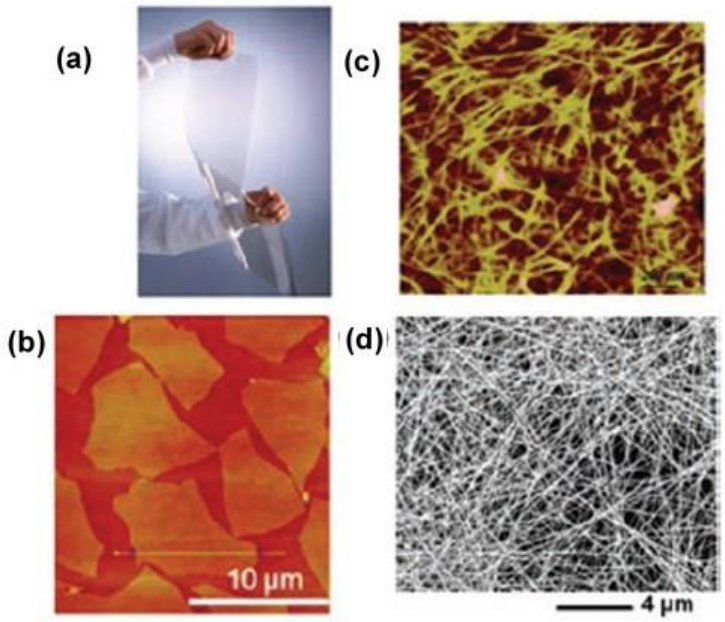

Figure 1: *Various in-development transparent conductors, reproduced with permission from [4]: (a) CNT film on plastic substrate, (b) Atomic Force Micrograph (AFM) of random CNT films, (c) AFM of random graphene flake film, (d) Scanning Electron Micrograph (SEM) of random Ag Nanowire Film.*

There are at least two approaches towards the goal of improving conductivity of random nanowire networks: (a) enhancing intrinsic conductivity of the material and of junctions between nanowires, and (b) optimizing the arrangement of the nanowire network, for a given nature of the material and of nanowire junctions. The work described here has pursued the latter approach, for which it is essential to develop a predictive model for the conductivity of a random network of metal nanowires. Due to the random nature of the system, attempts to create analytical models become exceedingly complicated. Many researchers have thus used Monte Carlo simulations to investigate electrical properties of metal nanowire networks and other rod-based materials [1, 9-14]. In many of these studies, it has been shown that adjustment of the rod orientation distribution has the potential to improve conductivity [1, 9-13]. Manipulating rod orientation removes rotational symmetry from the network; this has the potential to increase conductivity in a chosen direction at the expense of decreasing it along others. This tradeoff is desirable for many applications of transparent conductors which only require current flow in a single direction. Smartphone touchscreens, for example, have separate conducting layers for vertical and horizontal directions.

The specific findings of relevant literature are as follows. Du *et al.* used a computational model to study percolation properties of random 2D rod dispersions [11]. They also experimentally studied the effects of orientation on conductivity of 3D carbon nanotube composites, finding that a slight degree of

alignment improves conductivity. White *et al.*, in a follow up paper to [11], developed a more sophisticated computational model capable of calculating conductivity of 3D carbon nanotube networks, again finding that a slight degree of axial alignment improves conductivity [12]. Behnam *et al.* used simulations to analyze the dependence of resistivity of layered 2D carbon nanotube films on nanotube density, length, and alignment, among other factors [9-10]. Pimparkar *et al.* studied effects of orientation in CNT films, comparing the effects between long and short transistors [13]**.** More recently, Mutiso *et al.* adapted the conductivity model developed in [12] for 2D metal nanowire networks. They used the model to extract contact resistance in silver nanowire systems and find dependence of conductivity on area fraction of nanowires [14].

Thus far, all of the studies on the effects of orientation are on random CNT networks, which have significant differences compared to random metal nanowire networks. The smaller diameter of CNTs means that multiple 2D CNT films must be layered to create a film with conductivity comparable to that of a monolayer metal nanowire network, as accounted for by Behnam *et al.* [9-10]. CNTs films also contain a mixture of metallic and semiconducting rods. Furthermore, previous studies on effects of orientation have been limited in the types of orientation configurations analyzed. In particular, there is no systematic answer to questions about whether gains in conductivity can be achieved for different types of orientation configurations nor how to identify optimal configurations.

The work presented here addresses this gap in the field. It has two objectives: (a) to develop a general computational model for simulation of metal nanowire network conductivity and verify its accuracy, and (b) to use this model to discover how conductivity of random metal nanowire networks is affected by various nanowire orientation configurations. Three configurations of varying degrees of randomness were chosen. It was hypothesized that an increase in conductivity in a single direction would be achievable using any of the three configurations, with the increase being larger in more ordered configurations. It was also expected that the results for all three configurations would be similar in form, and that more ordered configurations would provide insight into results for less ordered configurations.

This research is important for a number of reasons. The model developed in this study is versatile and can be applied for investigation of other factors related to nanowire networks. Nanowire networks also share many properties with other percolation problems such as water flow, and the structure of this model could be emulated for investigating those systems. The specific methods for increasing performance of metal nanowire networks identified in this work will push adoption of metal nanowire films in technology, which will reduce costs by displacing ITO and allow for development of new materials and systems for electronics. The results also give new insight into the nature of the effect of orientation and open pathways for future investigations to better understand and use this effect.

2. Computational Methods

The computational model developed in this study was implemented in the Python® programming language. It was split into two major components: a random network generator, and a network conductivity calculator.

The network generator creates a network of randomly positioned and oriented 1D line segments in a finite, square 2D space. Each line segment represents a nanowire. The generator takes three values as input: a value each to define the size of the 2D space inside which the network is generated, the average length of the line segments, and number of line segments to be generated. Three random values are then generated for each rod to define its position and orientation. The network generator finishes with a percolation check – a clustering analysis is performed to see if a connected path exists in the horizontal direction across the sample. The generator then returns a Boolean variable to indicate whether the network has zero or non-zero conductivity, which indicates whether the conductivity calculator must be used.

The conductivity calculation is significantly more involved. The networks are considered to be composed of two types of ideal resistors: resistance of nanowires (R_{rod}) and resistance of junctions between nanowires (R_J). R_{rod} is calculated using the resistivity of silver, the most commonly used metal, as well as provided values for length and diameter of nanowires. All cases studied are for nanowires with a length of 35 μm and a diameter of 65 nm. This geometry is chosen based on silver nanowires which are commercially available from Seashell Technologies™ [15]. R_J is assumed to be constant, and is a fitted parameter found by comparing results of the model to experimental data. Various studies have shown that R_{rod} is approximately 2 orders of magnitude smaller than R_J [3-4, 7, 14]; the former is included in the model to increase versatility in analyzing similar systems where junction resistance may not be dominant.

To calculate conductivity of a specific system, the spatial arrangement of resistors is converted into an electrical circuit of resistors. Every intersection of two wires comprises two nodes, each with two wire resistors and one junction resistor entering it. Kirchhoff's Junction Law (balance of charge) yields an equation for each node. Applying Ohm's Law, these equations are rewritten into a matrix equation of the form

$$[A]\{\Phi\} = \{J\} \tag{1}$$

Where [A] is a matrix containing coefficients of voltages (the resistor conductivities), $\{\Phi\}$ is a vector containing voltages, and {J} is a vector containing net junction currents. Equation (1) is solved for the unknown voltages $\{\Phi\}$. Figure 2 shows the equation for a sample node, based on the defined voltages and resistances.

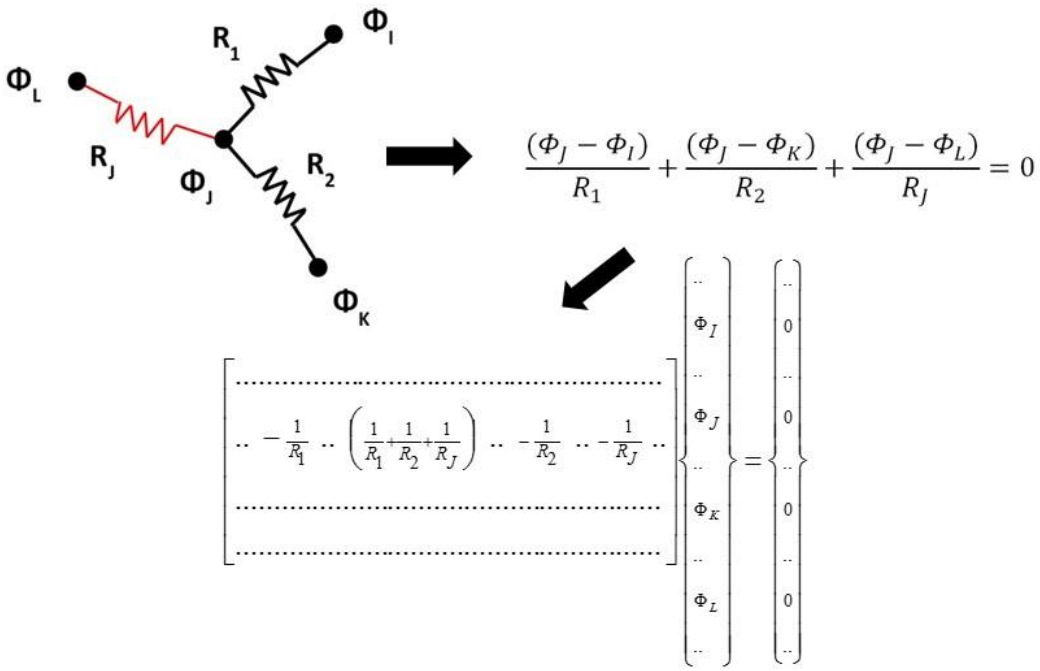

Figure 2: *Sample node and corresponding conservation of charge equation from Kirchhoff's Junction Law and Ohm's Law. Φ values are unknown voltages. R values are known, defined resistances. Each node has one junction resistor and two wire resistors entering it.*

The model takes advantage of the fact that [A] is symmetric and uses the banded Cholesky decomposition version of Gaussian Elimination to improve computational speed. Furthermore, junctions are numbered based on distance from the left electrode to minimize bandwidth of the matrix, saving space and reducing computation time. Once the matrix representing the resistor network has been created, an arbitrary voltage is applied from left to right across the sample. This is implemented in the model as a boundary condition on the matrix equation, which is then solved to yield the voltages at every node in the system. Figure 3 shows two samples of different concentration; (a) is at a concentration just above the critical concentration of percolation, C_p, where networks transition from non-conducting to conducting, while (b) is at a concentration far above C_p. Using computed voltage differences for wires that cross the boundaries, the model then sums current in all parallel branches that enter and exit the sample. Using Ohm's Law for the entire sample, the model then calculates resistance and conductivity of the network. The overall structure of the computational model is similar to models previously used for nanowires by Mutiso *et al.* [14] and for carbon nanotubes by Behnam *et al.* [9-10].

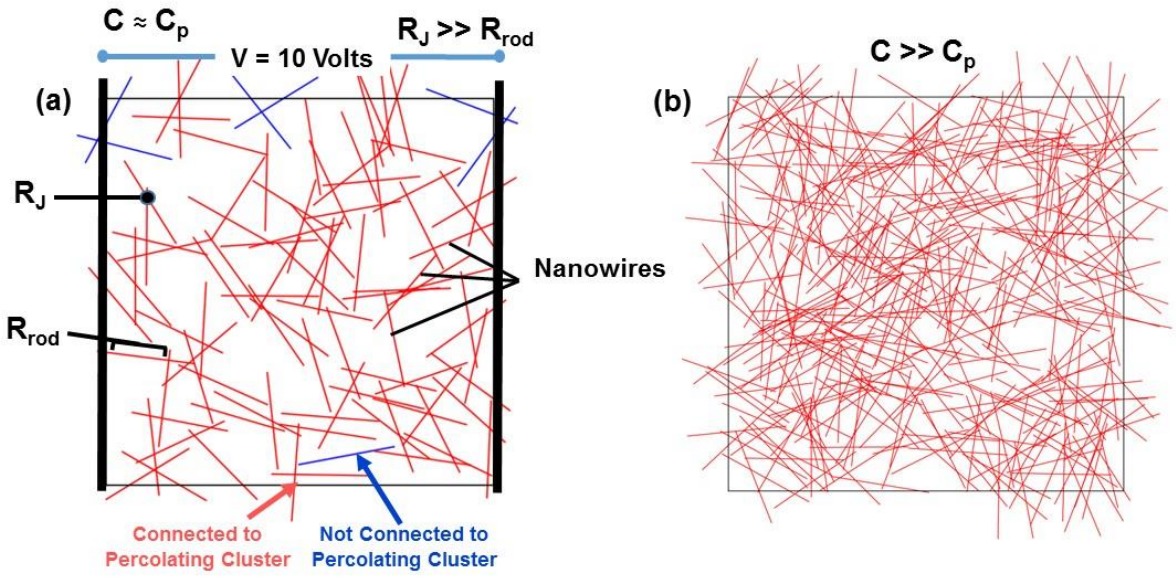

Figure 3: *Sample networks of nanowires of size 140 μm x 140 μm with (a) concentration just above critical percolation concentration ($C \sim C_p$), and (b) concentration much above critical percolation concentration ($C >> C_p$). The voltage is applied across the horizontal direction across the domain length. Reproduced from [1].*

There are several assumptions made in this model. The model is strictly 2D; rods interpenetrate and are not considered to have width in determining locations of intersections. This means that for very high concentration samples, the model will lose accuracy. Within the range of concentrations tested in this report, however, the model proves itself accurate. Furthermore, systems of high-enough concentration to break down the model's accuracy would likely be too low in transparency to be viable in most technologies as transparent conductors. In addition to those described earlier, several other standard approximations are used to increase the computational speed of the model. Boundary voltage conditions are applied by adding additional nodes of the desired voltage through very low resistance connections. This requires fewer changes to the matrix equation than applying an exact voltage to each desired node. Similarly, to handle singular matrices resulting when the system has disconnected clusters, every node is connected to a ground node through a very high resistance. Each of these approximations increases the efficiency and robustness of the model and it was verified that they do so without appreciably affecting accuracy. The assumption of constant junction resistance has been proven valid by Mutiso *et al*. [14]. While junction resistance is a fitted parameter, it is the only fitted parameter of the model.

From the values provided to the model, a raw length concentration C can be defined as the number density of rods (rods per unit area) multiplied by the length of each rod. The model then returns a raw conductivity k in Siemens. In order to generalize the data, these parameters are normalized. Because

junction resistance is dominant in the system, sample conductivity is normalized by multiplying it by R_J. This yields a conductivity value k_N that is independent of the specific value of junction resistance used, as long as junction resistance remains dominant. This means that the results presented here can be used by different experimentalists even if they use different methods to reduce junction resistance. Length concentration is normalized by multiplying again by rod length. This value C_N has been shown to be a universal indicator of percolation of 2D rod dispersions regardless of rod and sample size; a standard equation in percolation theory shows that the percolation threshold occurs at $C_{N,p} = 5.71$ [4, 16]. With this normalization, the results are thus valid for any set of rod and sample size used in experimental fabrication.

The model was first verified by using it to compute conductivity of a number of simple resistor networks for which it is also possible to calculate conductivity by hand. In order to verify further the accuracy of the model, a curve of k_N as a function of C_N was generated up to $C_N = 81$. This curve was then compared with previously published experimental data and the quality of the fit was examined. To conduct tests on the effects of the three orientation configurations studied, C_N was first fixed at 29.1 for all samples. In the first configuration, orientation of each rod with respect to the horizontal was chosen from a normal distribution, with standard deviation σ. In the second configuration, orientation with respect to the horizontal was chosen from a uniform distribution in the range (-θ, θ), while in the third, orientation with respect to the horizontal was chosen in the range [-θ] ∪ [θ].

3. Results and Discussion

Figure 4 shows normalized conductivity as a function of normalized length concentration in isotropic samples, with data both from the model and from a published experimental study by Mutiso *et al.* [14]. Each data point represents an average of 10 trials. A junction resistance of 2500 Ohms is used to normalize this experimental data, which matches the extracted contact resistance found by this study. The model clearly shows very good fit with the experimental data. The inset plot is a log-log graph of k_N as a function of $C_N - C_{N,p}$, taken only for samples well above the percolation threshold to avoid heavy fluctuations at lower concentrations (close to the percolation threshold). The plot is a straight line, which suggests power law dependence of conductivity on $C_N - C_{N,p}$ of the form:

$$k_N = \alpha(C_N - C_{N,p})^{\beta} \tag{2}$$

This equation is the accepted general form of dependence of conductivity on concentration [14]. A linear best fit indicates that $\beta = 1.73$, which agrees well with the accepted value of β for junction resistance dominated networks of 1.75 [14].

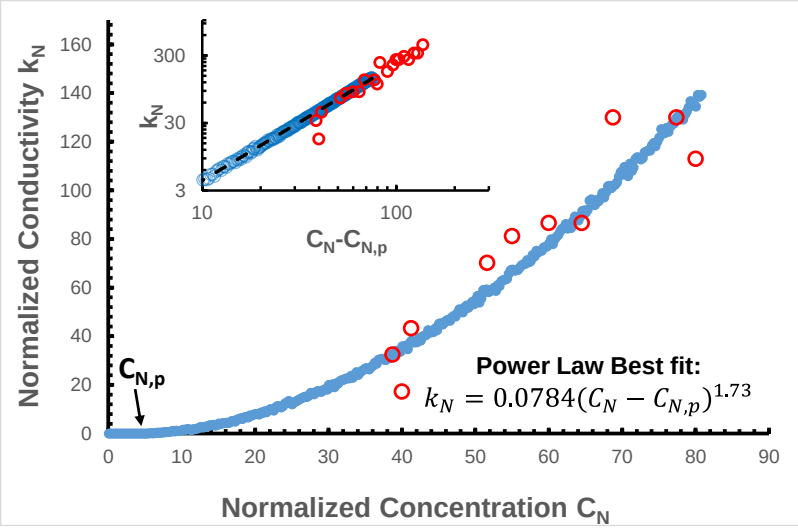

Figure 4: *Main plot shows normalized conductivity (k_N) versus normalized length concentration (C_N) from model (blue) and experimental data (red) [14]. Inset shows normalized conductivity (k_N) vs normalized concentration minus critical concentration (C_N - $C_{N,p}$) on a logarithmic scale. The relationship between k_N and (C_N – $C_{N,p}$) is presented using a power law best fit. Model matches experimental data well. Modified from [1].*

Because C_N is proportional to rod length, a power law relationship with k_N suggests that for a fixed length average, variation in rod length increases conductivity; longer rods would increase conductivity more than shorter rods would decrease it. The model can be used to test this hypothesis. Figure 5(a) is a plot of normalized conductivity as a function of σ. Here, rod length is chosen from a uniform distribution over the range (l_0 - Δl, l_0 + Δl). Average rod length always equals l_0. σ represents standard deviation of this distribution normalized by average rod length, or $\sigma = \frac{\Delta l}{\sqrt{3} l_0}$. Figure 5(b) shows an example for σ = 0.55.

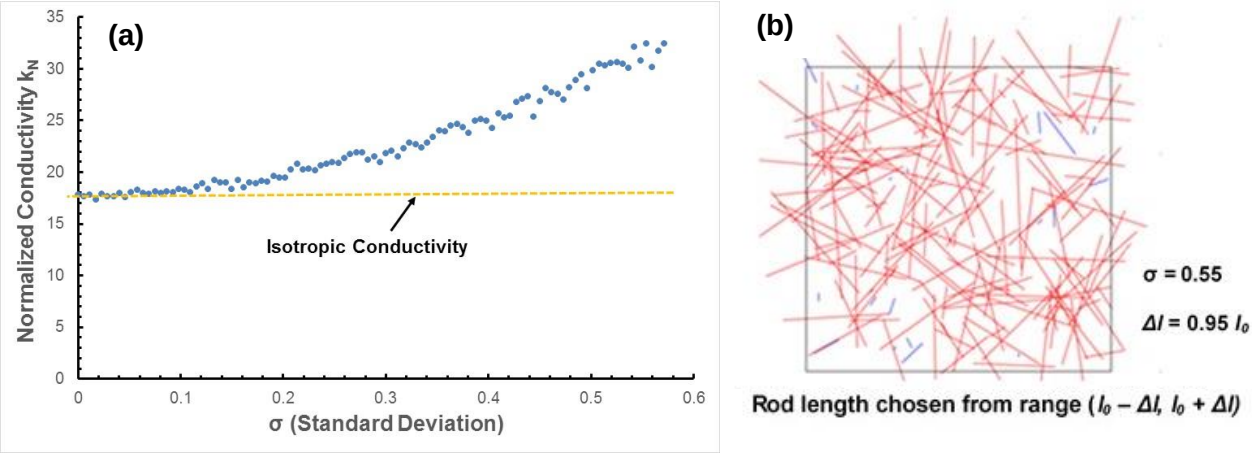

Figure 5: *Data showing (a) relation between normalized conductivity (k_N) and σ at C_N=29, where rod length chosen uniformly over (l_0 – Δl, l_0 + Δl) and $\sigma = \frac{\Delta l}{\sqrt{3} l_0}$ and (b) a sample network using this length distribution of size 140 μm x 140 μm at C_N=29 where σ = 0.55.*

As expected, an increase in conductivity is achieved for a fixed total length by varying rod length. This does not indicate, however, that nanowire manufacturers should use fabrication methods with wide variety in wire length; increasing the average length of nanowires yields a far larger increase. However, the results indicate that variances around an average rod length will not hurt performance. They also indicate that in networks with rods of varied length, longer rods play a larger role in determining conductivity and carry more current. Figure 6, a color map of current flow in networks, illustrates this effect. Rods carrying more current are wider and blue or red. Only long nanorods are highlighted. This is expected, as current traveling along long nanorods will encounter less high resistance junctions.

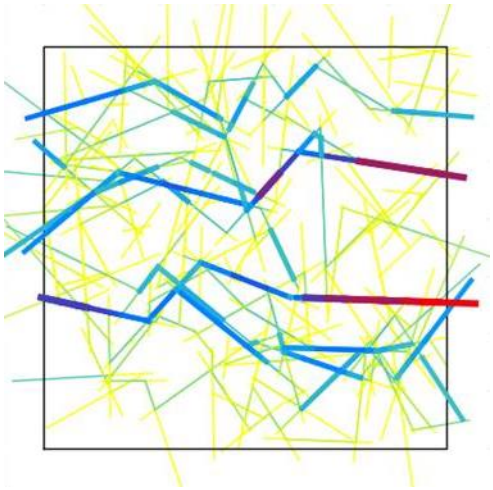

Figure 6: *Map of current flow in network with varied rod length. Dark, blue or red paths have high current density. Short rods are present, but only long rods have high current density. Conductivity more dependent on long rods as a result.*

The model can also be verified by observing how voltage decreases across a sample. Figure 7 is a 2D color map of voltage at each node in a high concentration sample. Voltage decreases uniformly along the direction in which it is applied, as expected. This test of reasonableness, combined with the strong fit with experimental data and previously published computational work, validates the model for use in investigations of the effect of orientation distribution.

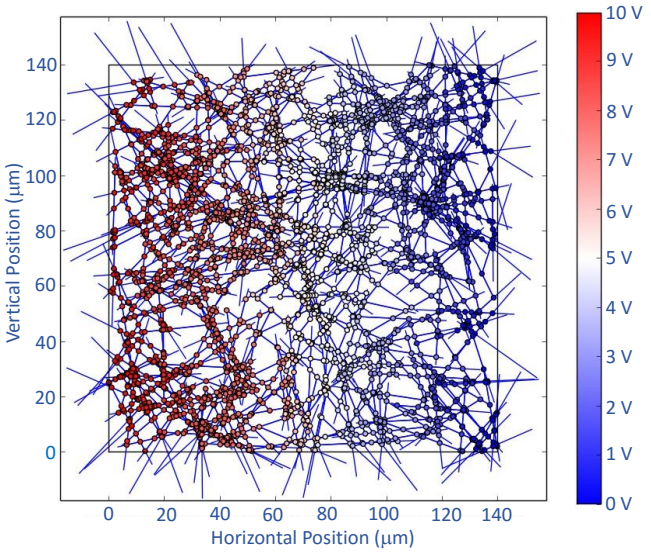

Figure 7: *2-D color map showing voltage at nodes for high concentration network (C ~ 5 C_p). Dots represent voltages at each node. Left border voltage is 10 V, right border voltage is 0 V. Reproduced from [1].*

Figure 8(a) shows normalized conductivity as a function of σ, where σ is the standard deviation of a normal distribution of orientations centered on a horizontal line L_h. Each data point represents an average of 20 trials. Figure 8(b) shows an example of one such sample with σ = 30°. It is important to note that when orientation is manipulated, networks are no longer rotationally symmetrical; conductivity measured parallel to L_h is not necessarily equal to conductivity measured perpendicular to L_h. For these plots, conductivity parallel to L_h corresponds to application of a potential difference from left to right across the sample, while conductivity perpendicular to L_h is found by applying a potential difference from top to bottom. All samples are generated at C_N = 29.1.

For large values of $\sigma \geq 80^o$, as expected, conductivity in either direction approaches the value for an isotropic sample. As σ becomes less than 80°, conductivity perpendicular to L_h begins to decrease, and continues to do so monotonically. However, conductivity in the same direction as L_h, surprisingly does not vary monotonically. It first increases with decreasing σ before decreasing, reaching a maximum around σ = 35°. The improvement in conductivity over the isotropic state is an approximately 20% gain over the isotropic control, a significant improvement in performance for applications which only require current flow in a single direction.

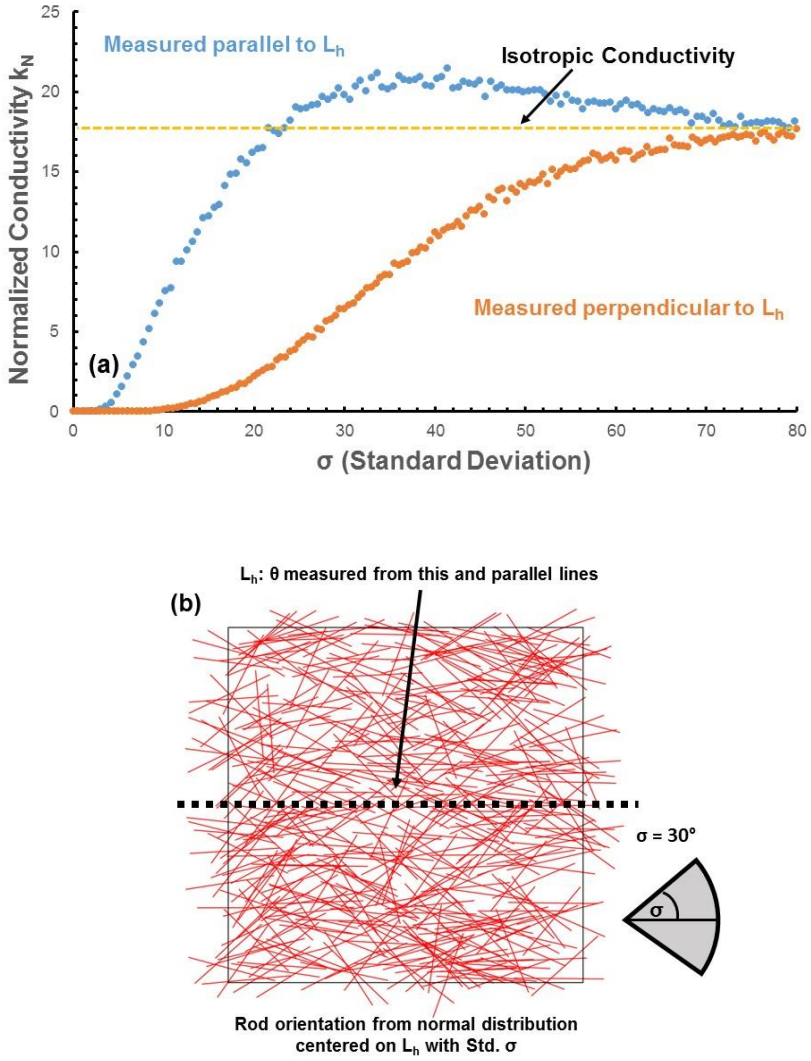

Figure 8: *Data showing (a) the relation between normalized conductivity (k_N) and σ at C_N=29, where rod orientation chosen from a normal distribution of standard deviation σ with respect to L_h, measured along and perpendicular to L_h, and (b) a sample network using normal orientation distribution of size 140 μm x 140 μm at C_N=29 where σ = 30°.*

Figure 9(a) shows data for the second distribution, in which orientation of the rods is restricted uniformly over (-θ, θ) from L_h. Each data point again is an average of 20 trials. Normalized conductivity is shown as a function of σ, where σ is the standard deviation of this distribution, and $\theta = \sqrt{3}\sigma$. Figure 8(b) shows an example of this configuration for θ = 45°. All other variables are kept the same as in Figure 7. The results for this more ordered configuration (Figure 9) qualitatively resemble those for the Normal distribution (Figure 8). As σ is restricted, i.e., θ is reduced from the isotropic state (θ = 90°, σ = 52°), conductivity perpendicular to L_h decreases monotonically, while conductivity parallel to L_h increases before

decreasing, reaching a maximum around σ = 33°, which corresponds well with the normal distribution. This increase in conductivity is slightly larger than that of the normal distribution, at around 25%.

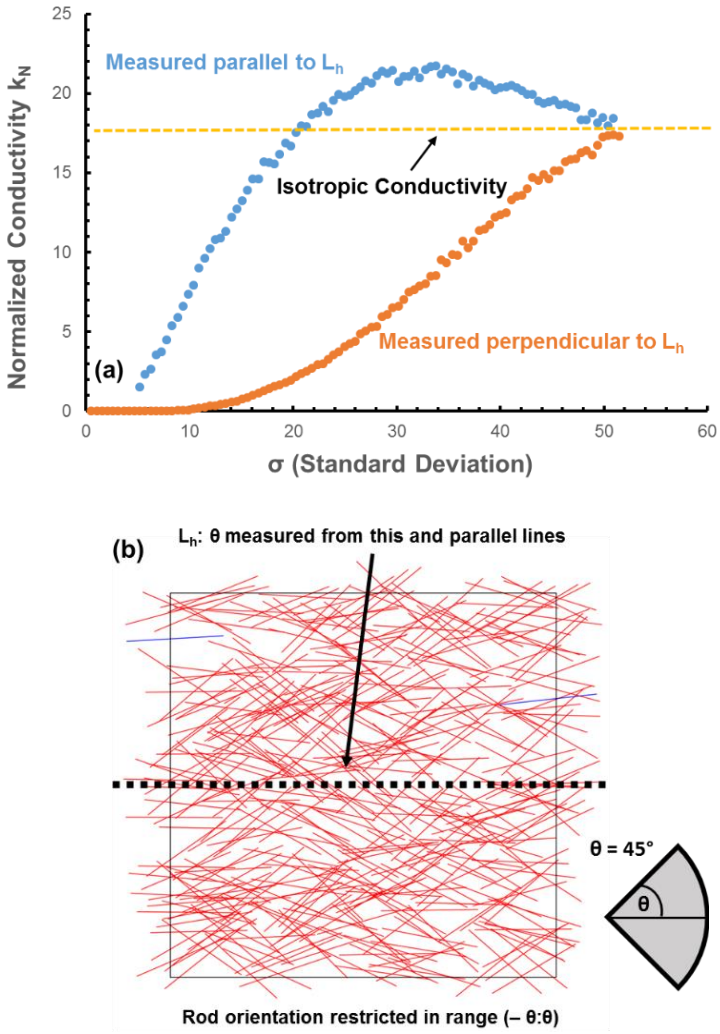

Figure 9: *Data showing (a) the relation between normalized conductivity (k_N) and σ at C_N=29, where rod orientation is distributed uniformly over (-θ, θ) with standard deviation σ with respect to L_h, measured along and perpendicular to L_h, and (b) a sample network using uniform orientation distribution of (-θ, θ) of size 140 μm x 140 μm at C_N=29 where θ = 45°. Modified from [1].*

The first two data sets can be understood as resulting from the action of two competing effects that result from decreasing θ. As θ is reduced, the number of intersections and number of parallel paths decreases, reducing conductivity. At the same time, the number of junctions the current must travel through decreases (parallel to L_h) or increases (perpendicular to L_h). This increases conductivity parallel to L_h and decreases conductivity perpendicular to L_h. Figure 10 shows a color map of current density in different nanowires which illustrates this contrast (Thick wires colored blue carry higher currents; thin wires colored

yellow carry lower currents; occasional red wires carry the highest currents). Figure 10(a) shows an isotropic sample with voltage applied left to right, while Figure 10(b) shows a sample with the same concentration and voltage direction with highly oriented nanowires. The right sample clearly has fewer current carrying paths, but each path also has fewer junctions. The exact shapes of the curves are determined by the way these effects compete and their relative magnitudes.

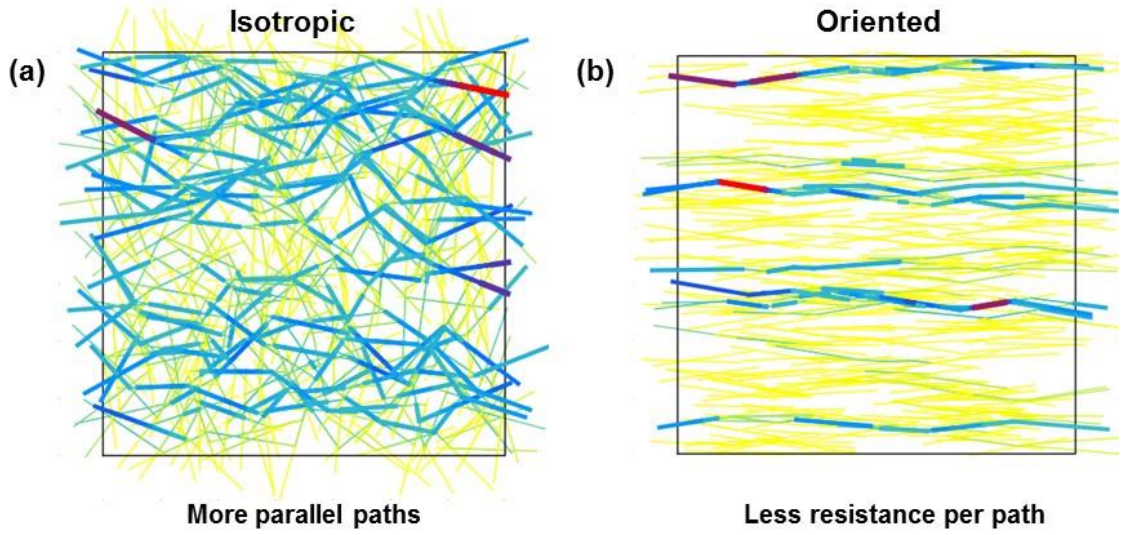

Figure 10: *Maps of current flow in (a) isotropic networks and (b) oriented networks. Dark, blue or red paths have high current density. Isotropic networks have more parallel paths, but more resistance per path. Oriented networks have fewer parallel paths, but less resistance per path. Voltage is applied left to right.*

Figure 11(a) shows data for the final orientation configuration, in which rod orientation is restricted in the range $[-\theta] \cup [\theta]$ from L_h. Normalized conductivity is shown as a function of σ, where σ is the standard deviation of this distribution and $\theta = \sigma$. Figure 11(b) shows an example of this configuration with $\theta = 45°$. Note that for any value of θ taken with respect to L_h, the value $90° - \theta$ is exactly equivalent when taken with respect to a line perpendicular to L_h. For the case where $\theta = 45°$, it does not matter whether conductivity is measured parallel or perpendicular to L_h. For any other value of θ with conductivity measured parallel to L_h, an equivalent network is obtained by taking $90° - \theta$ and measuring conductivity perpendicular to L_h. This is why the curves exhibit symmetry about $\theta = \sigma = 45°$.

One of the surprising results of this work is that the form of these results differs significantly from the previous two distributions. Despite the configuration being by far the most ordered of the three, no performance gain over an isotropic sample is achieved for any value of σ. A sample with $\sigma = \theta = 30°$ appears to be exactly equivalent in conductivity to an isotropic sample; any other value of θ causes a decrease in conductivity.

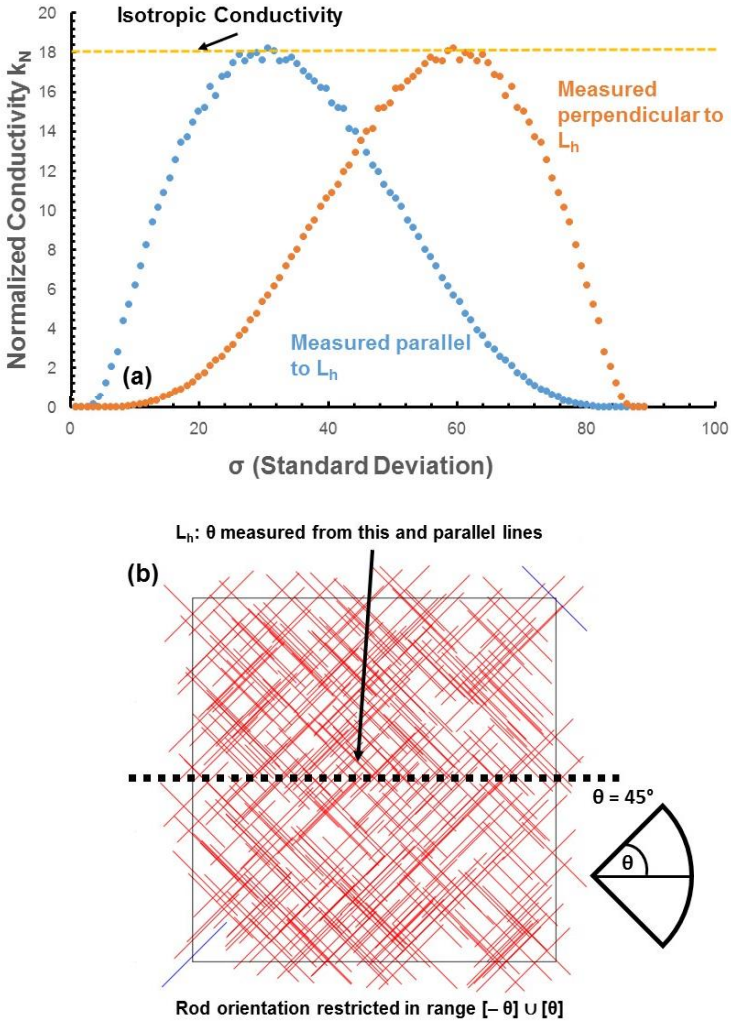

Figure 11: *Data showing (a) the relation between normalized conductivity (k_N) and σ at C_N=29, where rod orientation is distributed over [-θ] ∪ [θ] with standard deviation σ with respect to L_h, measured along and perpendicular to L_h, and (b) a sample network using orientation distribution over [-θ] ∪ [θ] of size 140 μm x 140 μm at C_N=29 where θ=45°. Modified from [1].*

The original hypotheses regarding the effects of orientation configurations on metal nanowire network conductivity were thus partially verified. Increases of similar form and magnitude were observed for the first two orientation distributions, Normal and Uniform. These increases are significant, and suggest that it will be useful to develop experimental methods to achieve some orientation. The strength of the computational model is that it shows the existence of an optimal degree of orientation and, further, provides quantitative estimates. As such, it can push further adoption of metal nanowire networks in electronics by showing how to optimize properties by controlling orientation. The most ordered configuration, however, unexpectedly showed no increase in conductivity, demonstrating that the nature of the effects of orientation

is more complex than initially realized. More ordered configurations are not necessarily superior in performance; interaction between various effects of random orientations seems to have a beneficial effect in certain cases.

The results from the Normal and Uniform distributions are qualitatively similar in form and magnitude of performance increase demonstrated by Behnam *et al.* and Pimparkar *et al.* for CNT films made of multiple 2D layers although specific values differ [9-10, 13]. They are also the first complete confirmation that rod orientation can increase conductivity of metal nanowire films. Moreover, our normalization renders the results applicable over a wide range of nanowire length and conductivity. The presentation of configurations of different degrees of randomness and attempts to illustrate the causes of the results are the most in depth examination of the nature of the effects of orientation on 2D rod networks.

4. Ongoing and Future Work

The results of this study open several avenues for future investigation. A simple fabrication method must be developed to partially orient nanowires in ways similar to those demonstrated in this study, in order to achieve the performance gains shown. Research conducted by the Competition Entrant is currently ongoing on the possibility of using electric fields to induce dipoles and spin nanowires towards a desired axis. This has been successfully achieved using high frequency alternating frequencies in aqueous suspensions of metal nanowires [17]. A similar method is being investigated for integration with the commonly used, scalable Mayer rod coating process. Figure 12 shows the concept; electrodes located above and below the deposition substrate are used to apply an electric field in the direction of desired alignment. As nanowires are deposited from solution, this electric field is intended to induce dipoles and cause slight alignment before nanowires dry and lose rotational freedom.

The computational model developed in this work is a versatile and generally useful tool for investigating other properties of metal nanowire networks. Various other variables could be tested to look for significant performance improvements. In order to address one of the major assumptions of this study, investigations could be made into the properties of metal nanowire networks when R_J is not dominant; these results would be particularly applicable in conjunction with experimental methods to reduce junction resistance.

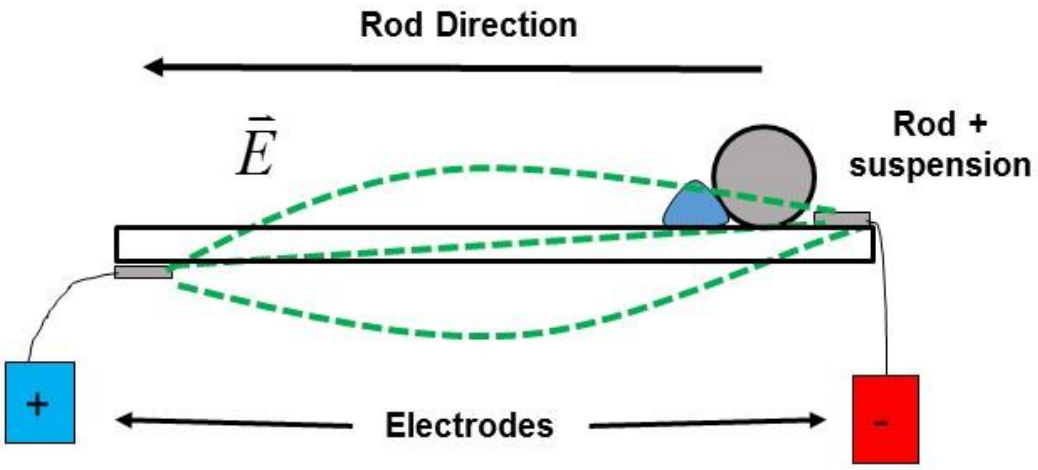

Figure 12: *Proposal for experimental implementation of nanowire orientation. Mayer rod (right) rolls nanowire suspension across substrate while electric field is applied in direction of desired alignment by electrodes. Dipoles are induced and nanowires turn briefly before suspension dries.*

Lastly, there remain many questions about the nature of the effects of rod orientation on percolation and network conductivity. Analytical derivations of the results for the most ordered configuration could yield deeper insight for some of these peculiarities, such as why $\theta = 30°$ corresponds exactly to conductivity of an isotropic network. More orientation configurations could be tested to attempt to identify an ideal configuration, and the characteristics of ideal configurations. These results could then be used to identify the best orientation configuration that is also easily manufactured for application in the aforementioned technologies.

5. Conclusions

In summary, metal nanowire networks show great potential for application in various forms of technology. An efficient and versatile computational model for metal nanowire transparent conductors was developed and verified against published experimental data. The model was also used to show that variances on an average nanowire length increase conductivity. In addition, with this model, the first results on dependence of metal nanowire network conductivity on various orientation configurations were obtained. It was shown that significant improvements in conductivity can be achieved by manipulating rod orientation, for technologies where current flow is only needed in a single direction. The results, however, indicate that the nature of these effects is complicated; more ordered orientation configurations do not necessarily exhibit superior performance. Moving forward, the work shows the need for development of experimental techniques to implement and achieve these performance gains. As this occurs, metal nanowire

transparent conductors can move closer to fully displacing ITO and furthering the growth of various types of electronics.

6. Reference of Self-Publication

Much of the content of this report has been published in [1], of which I am the first author. Language dispersed throughout the report is reproduced from [1]. Figures 3 and 7 were published originally in [1] and were reproduced identically. Figures 4, 9, and 11 were originally published in [1] but were modified for this report.

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