Patterning Vertically Aligned Single Walled Carbon Nanotubes

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Single-walled carbon nanotubes (SWNTs) are considered one of the most promising materials for next generation optical and electronic devices, but their potential is currently limited by the gap between their high-performance nanoscale properties and their less impressive macroscale performance [1]. Previously, using water vapor treatment to form vertically aggregated SWNT walls on a buckypaper bottom in a micro-honeycomb network (μ-HN) has been successful in creating a material with lower sheet resistance and higher optical transmittance than buckypaper [2]. However, it is very difficult to control the size and uniformity of SWNT walls using only the evaporation and condensation of water as a building tool. In order to provide a template for this naturally occurring vertical aggregation, we investigated using micro-scale patterns created by photolithography to mechanically stamp forests of VA-SWNTs into the desired form, prior to water treatment. We found that these patterned materials exhibit greater transparency and lower sheet resistance than both unstamped and untreated VA-SWNTs, which is promising for applications as a transparent conductor and in Si-SWNT solar cells. Since parameters such as cell size and shape, force applied, and cell depth can be better controlled with patterning, perhaps technique is promising for further optimization of μ-HN morphology for a wide variety of applications.

[1] M.F. De Volder *et. al*. Science 535-539 (2013).
[2] K. Cui *et. al*. J. Phys. Chem. Lett. 2571 (2013).

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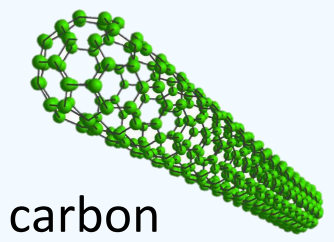
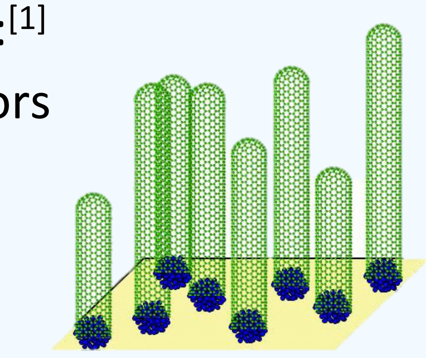
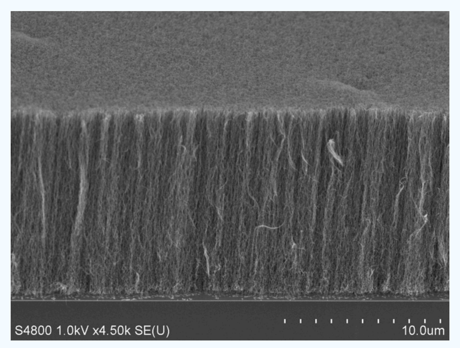
Background



Vertically Aligned Single walled carbon nanotubes (VA-SWNTs) have potential for multiple applications:[1]

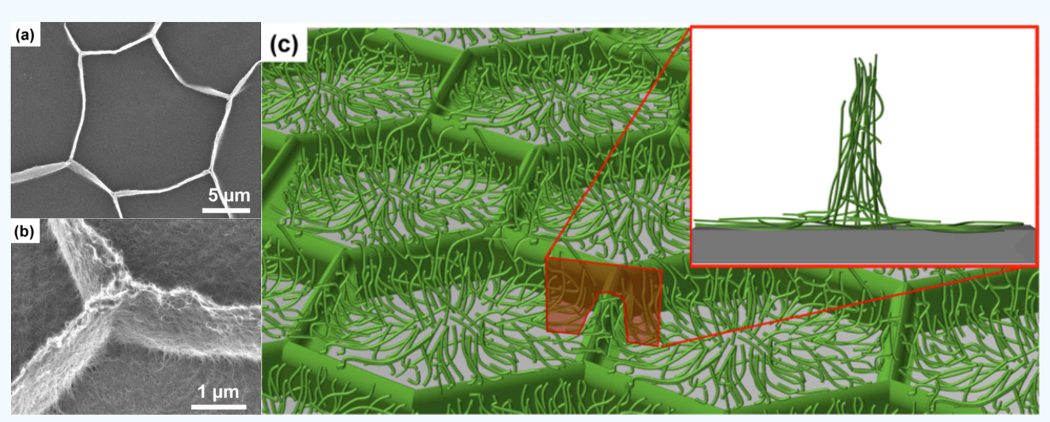
- Transparent conductors
- Si-SWNT solar cells





Self-Assembled Micro-Honeycomb Network:[2]

- Water vapor treatment used to form vertically aggregated SWNT walls
- Lower sheet resistance and higher optical transmittance than randomly oriented SWNT film



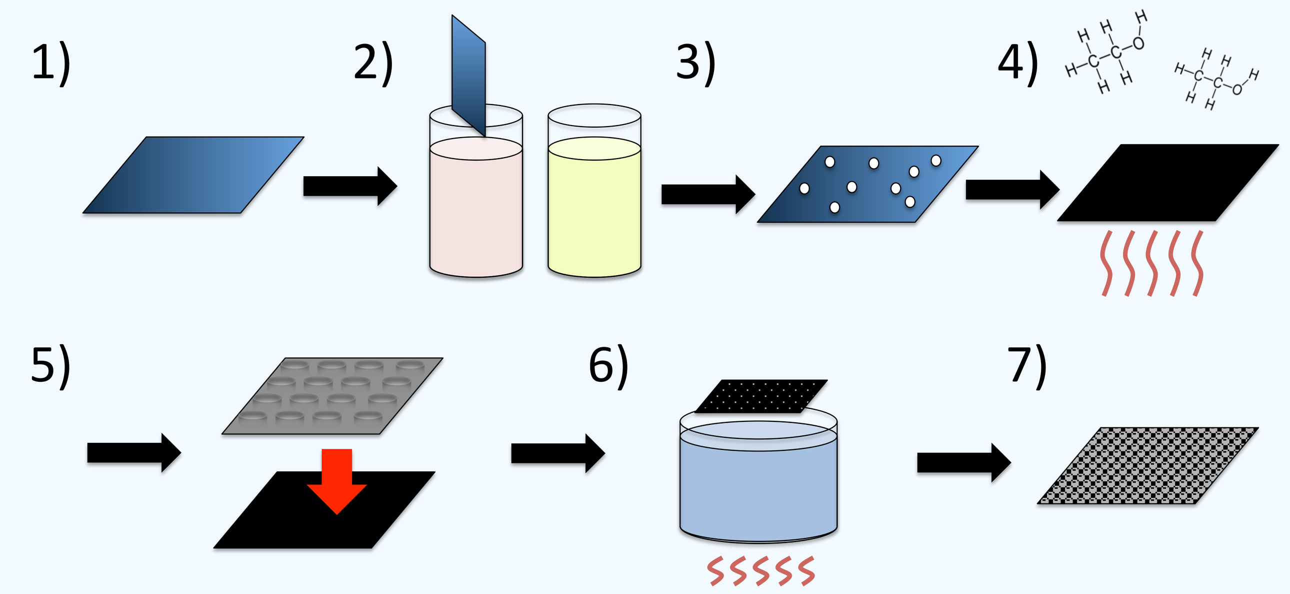
Research Question

Can the material properties of VA-SWNTs be improved by patterning the surface and combining the water treatment technique?

Challenges:

- Size and uniformity of aggregated SWNT cell walls are difficult to control using only the evaporation and condensation of H_2O.
- An automated process to apply a uniform force distribution must be developed.
- Morphology must be improved in order to optimize both optical transparency and electrical conductivity.

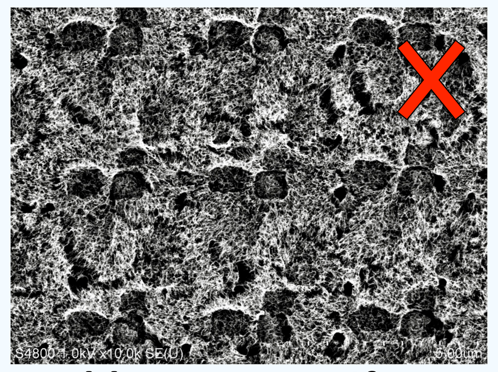
Synthesis of Patterned VA-SWNTs



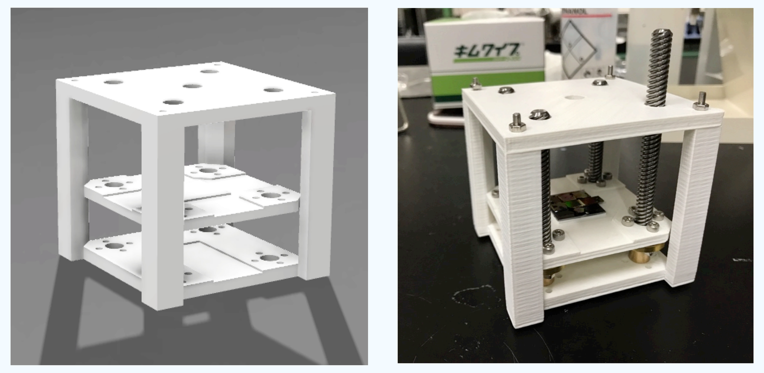
1) Si/SiO_2 or quartz substrate
2) Dip-coating in Co/Mo solution
3) Thin layer of metal catalyst
4) Chemical vapor deposition (CVD) of VA-SWNT at 800 ˚C with ethanol.
5) Microstructural development using mechanical stamping of photolithography derived patterns
6) Water treatment at 80 ˚C for 5 seconds (x25)
7) Patterned single walled carbon nanotube forest

Design and Fabrication of Mechanical Press

- Designed 3D-printable stamping mechanism in Autodesk Fusion 360 to uniformly press lithography patterns into VA-SWNTs
- Fabrication at the Google Garage at Google Headquarters



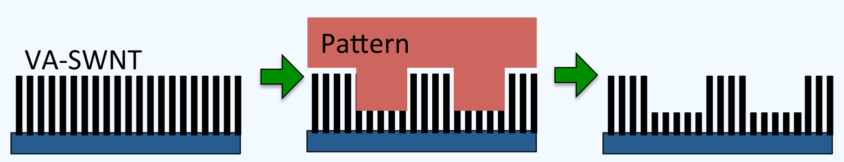
Problem: *Non-uniform stamping*

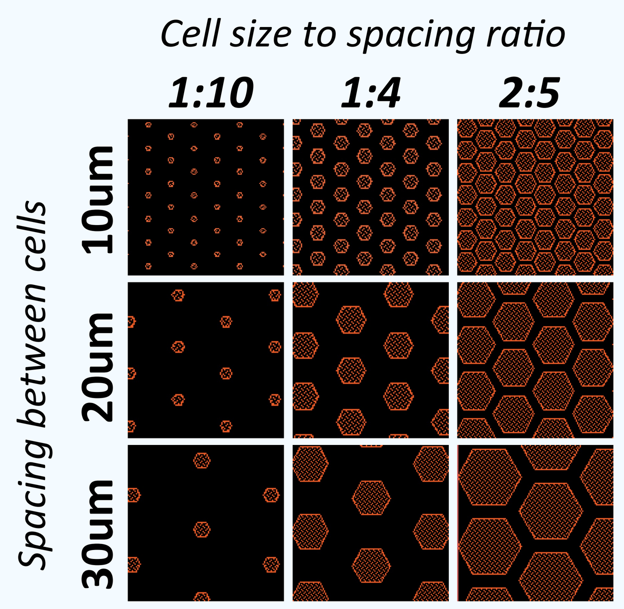


Solution*: Developed automated press*

Custom Photolithography Patterns

- Used LayoutEditor C++ Macros to design hexagonal patterns of varying cell size and spacing
- Fabrication of 24 micro-patterns on Si/SiO_2 wafer using negative resist photolithography

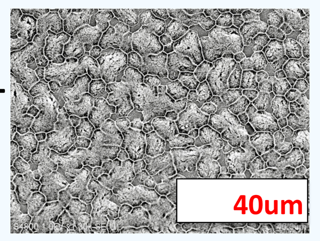


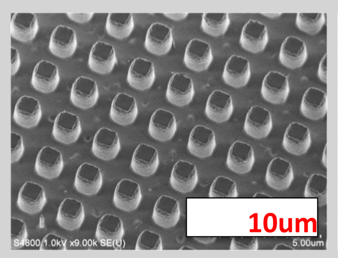
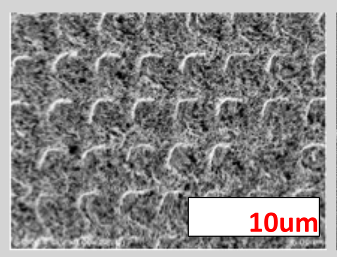
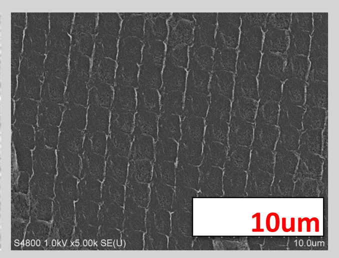
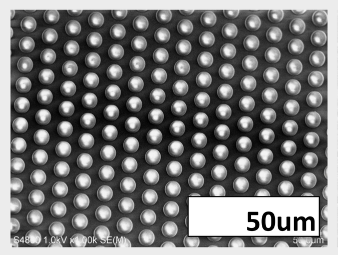
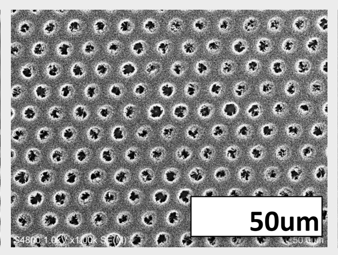
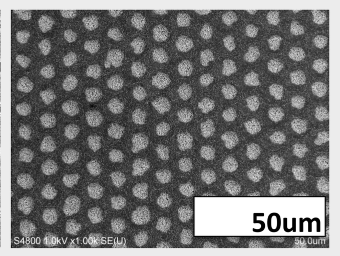
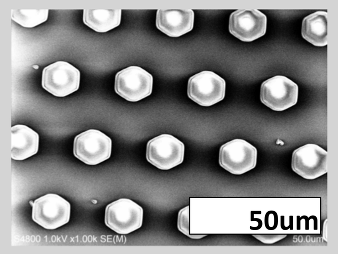
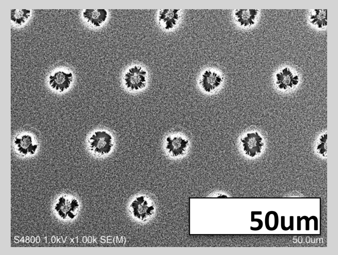
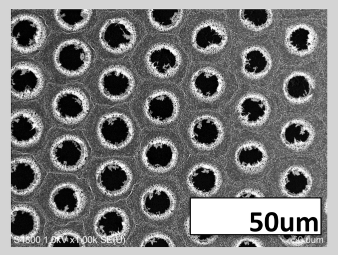


VA-SWNT Morphology

Scanning Electron Microscopy

Unpatterned VA-SWNT after water treatment



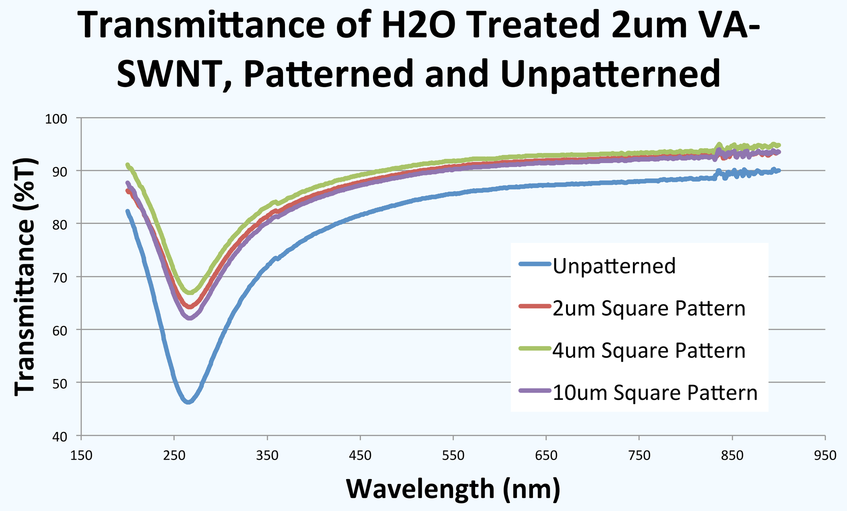
	Lithography pattern	Stamped, Untreated	Stamped, Treated
2um (square)			
10um (hexagon)			
30um (hexagon)			

Optical Transmittance

UV-vis-NIR Spectroscopy

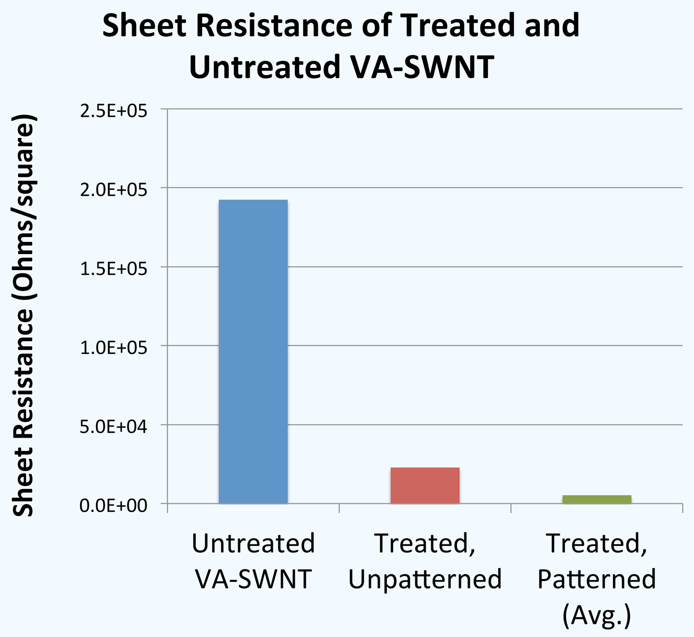
Average % Transmittance for Treated VA-SWNTs at λ=550nm

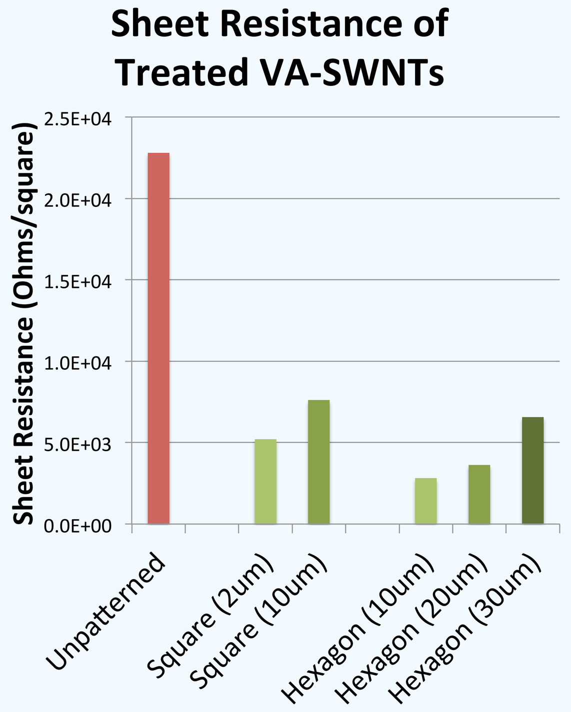
VA-SWNT forest height	10um	2um
Unpatterned VA-SWNTs	42.50%	85.60%
Patterned VA-SWNTs	44.00%	90.90%



Sheet Resistance

Four Point Probe Method





Conclusion

We successfully increased the uniformity of the VA-SWNT microstructure, leading to significant improvements in optical transmittance and sheet resistance.

- 8x improvement in electrical conductivity compared to self-assembled micro-honeycomb structures
- 68x improvement compared to as-grown VA-SWNT forests.
- Significantly higher optical transmittance as compared to both self-assembled and as-grown structures.
- Success of photolithography patterning suggests unlimited potential in developing highly designed vertically aggregated nanotube structures.

This new patterned material demonstrates promise for use in a wide variety of applications, including solar cells, transparent conductors, and photovoltaics.

Future Work

- Further optimize properties of VA-SWNTs by varying size and spacing parameters
- Direct application of material for use in Si-SWNT solar cells

References

[1] M.F. De Volder *et al*. Science 339, 535-539 (2013).
[2] K. Cui *et al*. J. Phys. Chem. Lett. 4, 2571 (2013).

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