



OPTIMIZING CARBON NANOTUBE CONTACTS FOR USE IN ORGANIC PHOTOVOLTAICS

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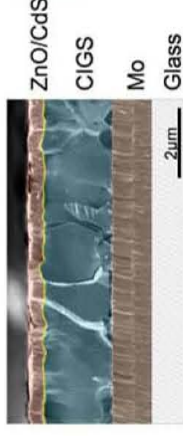
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Transparent Contacts in PV

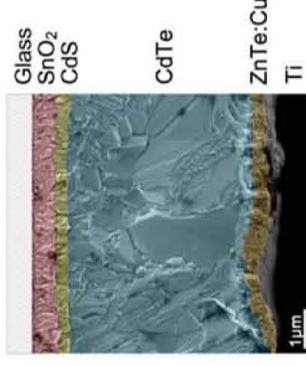
- Thin Film Devices
 - CdTe (16.5%) – TC sees 600°C
 - CIGS (20%) – TC must be grown at room T
- TCOs
 - ZnO:Al, SnO₂:F, In₂O₃:Sn, Cd₂SnO₄
- TCs must meet different requirements in each technology
- Successful demonstration of SWNT electrodes in thin film devices

13% w/CNT



CIGS	ZnO, ITO - 2500 Å
	CdS - 700 Å
CIGS	1-2.5 μm
	Mo - 0.5-1 μm
	Glass, Metal Foil, Plastics

12% w/CNT

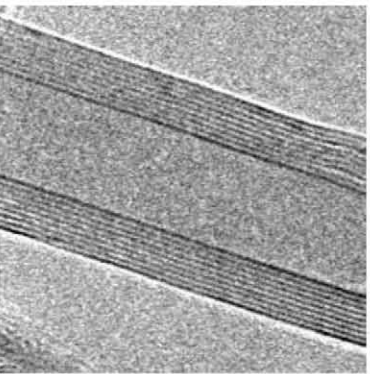


CdTe	Glass
	SnO ₂ , Cd ₂ SnO ₄ - 0.2-0.5 μm
	CdS - 600-2000 Å
CdTe	2-8 μm

www.nrel.gov/ncpv/thin_film/docs/wc4papernoufi_.doc
 CIGS - Contreras, J. Phys. Chem. C, 14045, 2007;
 CdTe - Barnes, APL, 243503, 2007

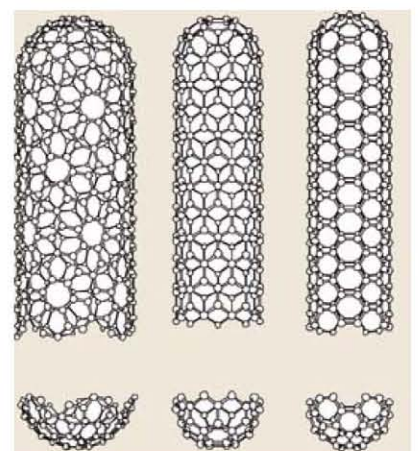
Carbon Nanotube Basics

Multi-wall tubes



Baughman, Science 287 2002

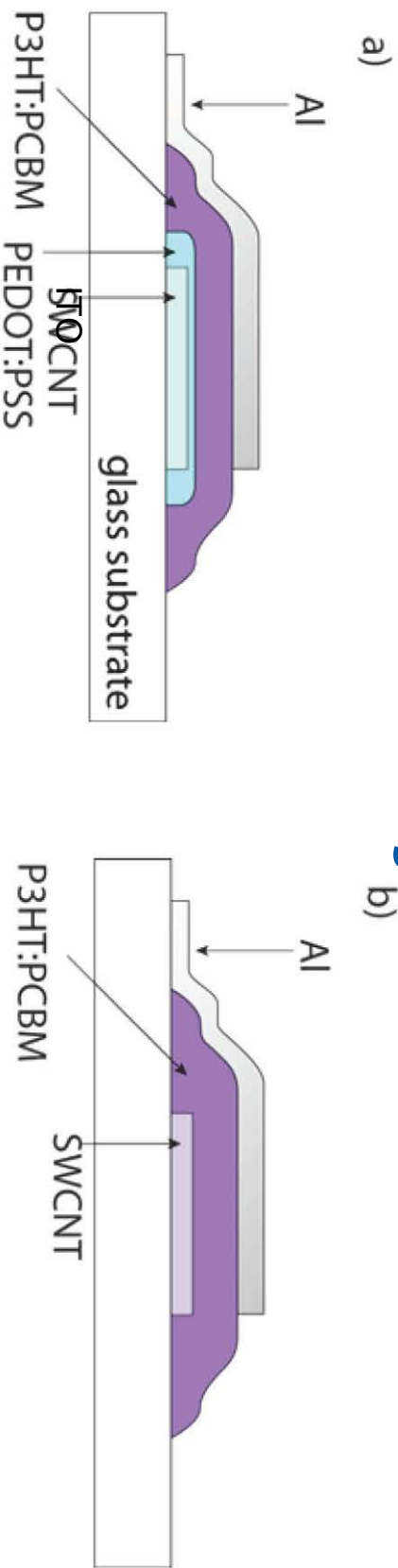
Single-wall bundle



- Many synthesis methods
 - CVD, Arc, HiPCO, laser vaporization
- Extensive post-processing
- Impurities
- Multi vs. Single Wall
- Random chirality distribution
 - 1/3 metallic, 2/3 semiconducting

OPV Device Structures

Bulk Heterojunctions



Short diffusions lengths would require impractically thin absorber layers in a “stacked” heterojunction (BHJ $\sim 300\text{nm}$ thick)

Mix P3HT and PCBM in a 1:1 ratio to create a “bulk” heterojunction

P3HT carries **holes** to the **ITO** side, PCBM transports electrons to Al

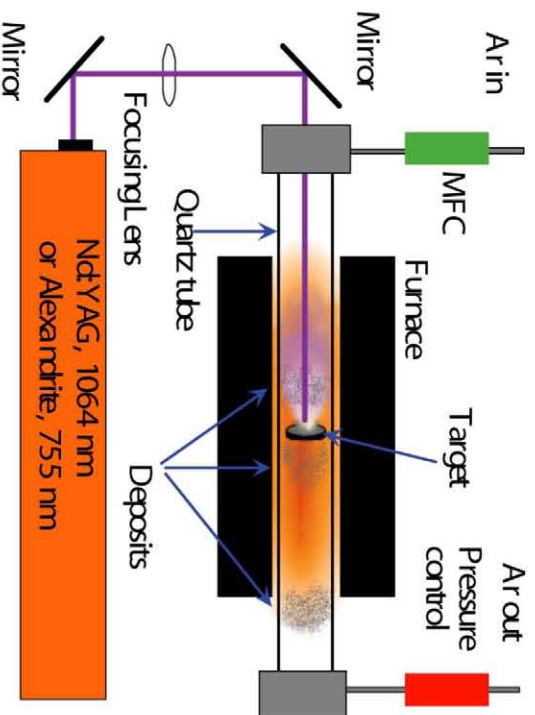
OPV Device Results:

J. van de Lagemaat, T. M. Barnes, G. Rumbles et al.,

Applied Physics Letters **88** (23), 3 (2006).

Early SWCNT Production at NREL

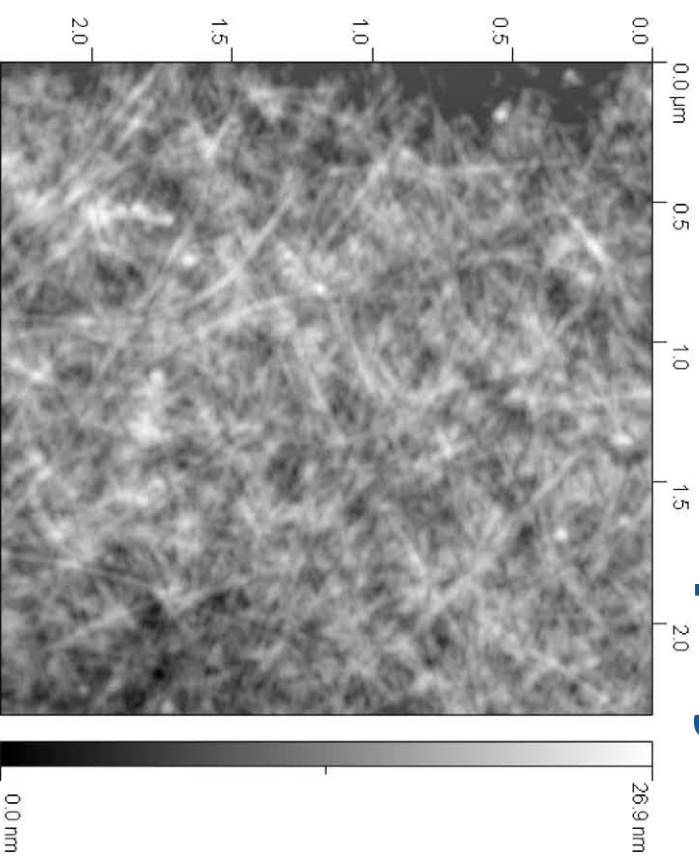
- All “TCO” work so far uses laser tubes
- $1\text{nm} < d < 1.4\text{ nm}$; all SWCNT
- PLV tubes are very long with low defect density (Raman D/G $\sim 1/190$)
- Films formed by vacuum filtration/ membrane transfer



NREL Pulsed Laser Vaporization

Wu, *Science*. **305**, 1274 (2004)

Scalable Production: Ultra-sonic spray



Metrics: Transparency, Conductivity, Stability

Parameter Matrix

Purification: metals, amorphous C

Surfactant: SWCNT dispersion, bundle size

Sonication: SWCNT length, bundle size, defects

Post Processing: surfactant removal, doping

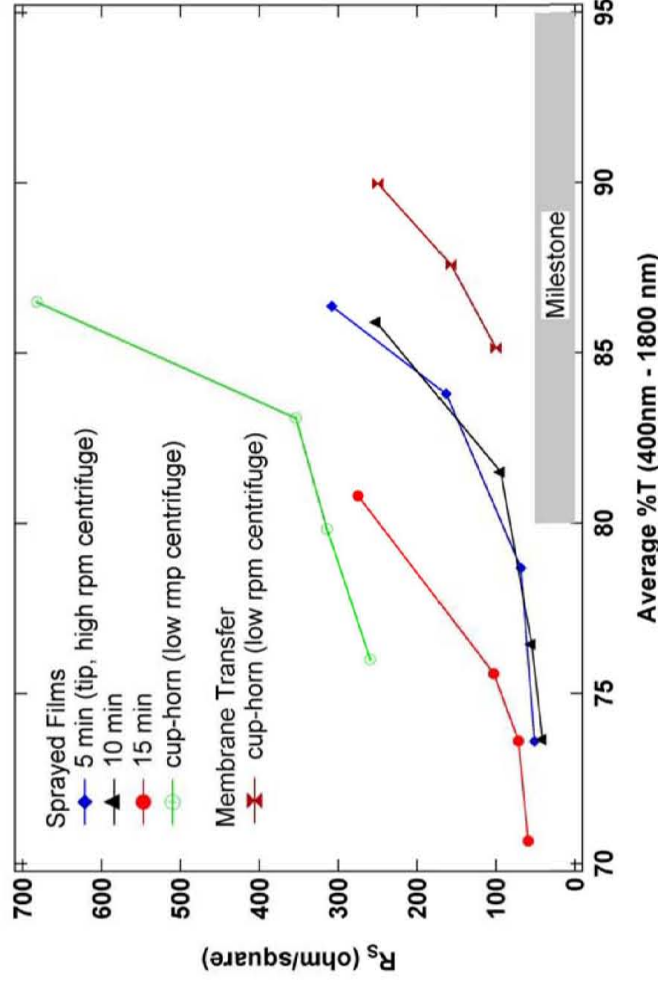
Surface Functionalization: wetting, drop formation



1 x 4 inch

Ink Formulation for Ultrasonic Spray

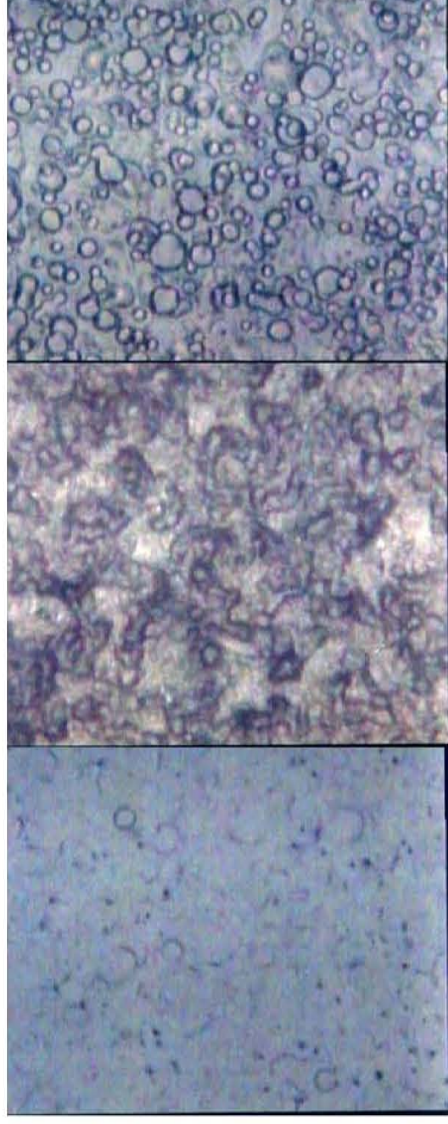
- Aqueous inks
- Ink sonication
- Tube purification/
starting material
- Surfactant choice is key
 - Morphology
 - Conductivity
 - Removal



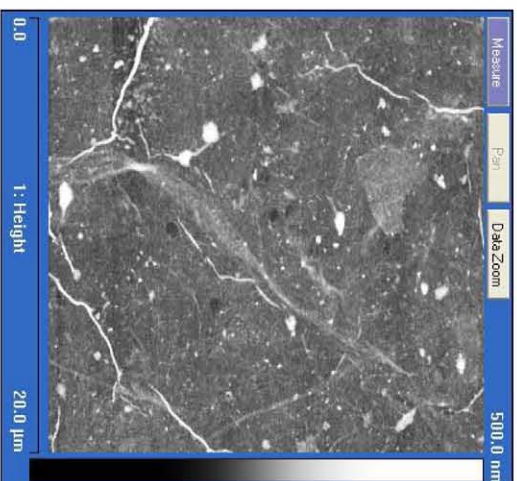
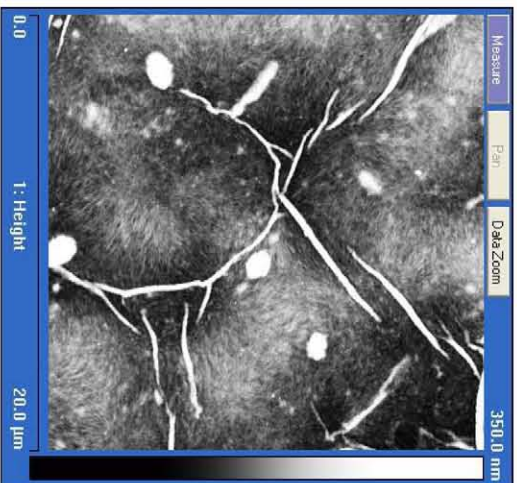
Best

OK

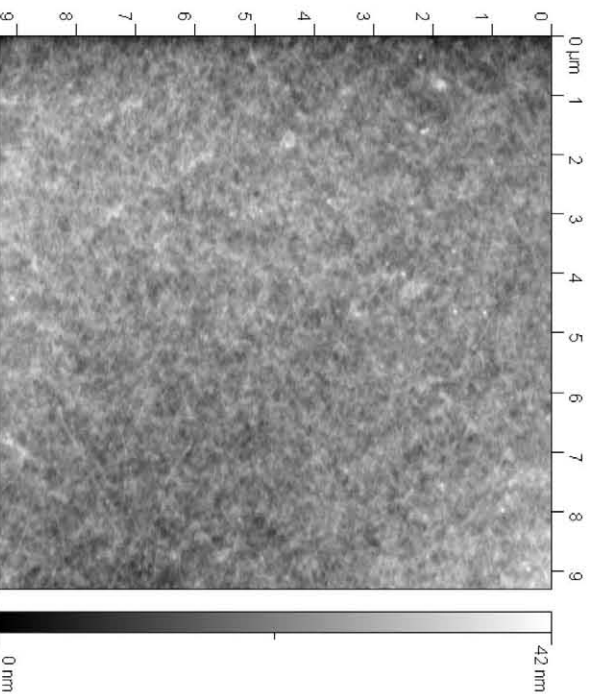
Bad



Sprayed vs. Membrane Transferred



- Large scale roughness in membrane films
- Possible texturing from membrane
- Wrinkling



- Sprayed films are more uniform
- ~70 Ω /sq, 80% T (400-1500 nm)
- Smooth and featureless
 - Potential for fewer shorts in devices
 - Fewer apparent impurities

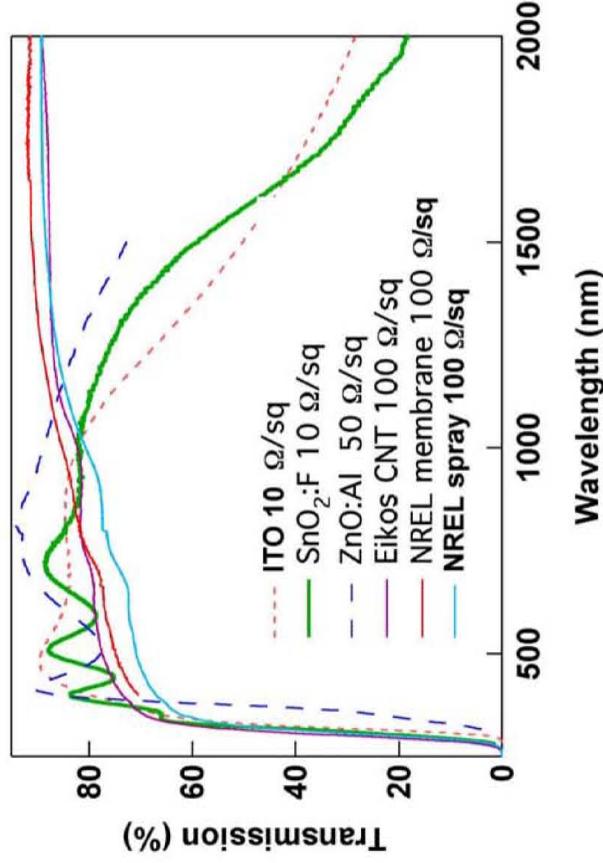
Compare TCOs with SWCNTs

- Transparent SWCNT
 - Spaghetti-like network
 - ~50 nm thick
- Hole conducting

Seebeck V (μ V)

Sample: 50 Ω /sq CNT
Temp: 300.4 K
Seebeck coeff.:
16.5 $\pm$ 1.4 μ V/K

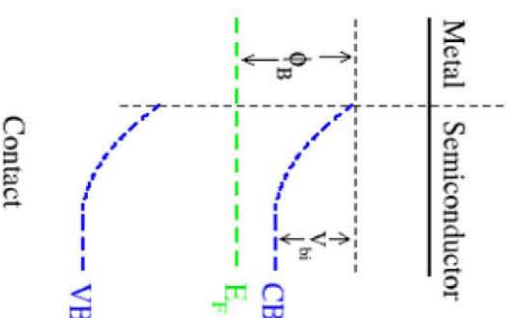
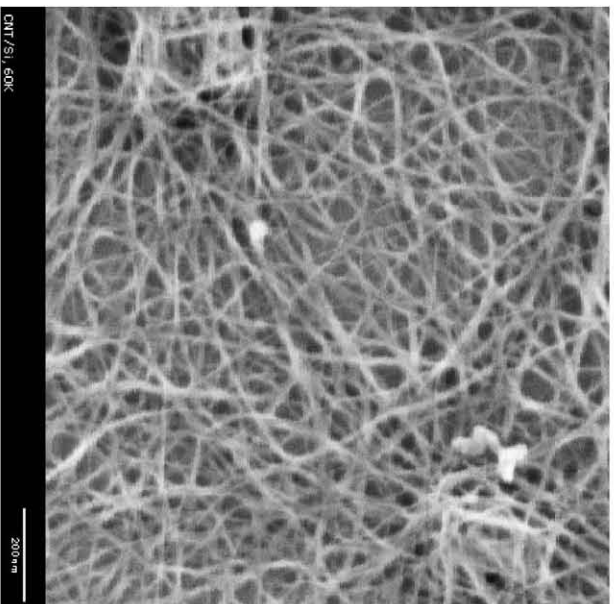
“p-type”



Seebeck DT (K)

- Functional in solar cells (w/ performance drop)
- Need to improve R_s/T
 - Doping, separations,
 - improved deposition, purification processes

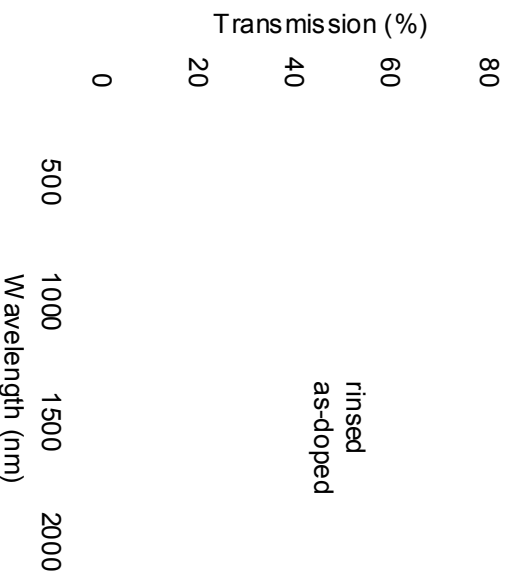
Conductivity in “Bulk” Networks



Schottky barriers are thought to exist between M and S tubes and limit μ

- Mixture of metallic (1/3) and semiconducting (2/3) tubes
 - Tubes/bundles have high aspect ratio in “good” networks
 - Measured “p” is low, but networks behave like degenerate semi
 - Mobility of the network is very different from individual tubes
 - $\mu_{H, \text{tube}} \sim 1000\text{-}10000 \text{ cm}^2/\text{V-s}$
 - $\mu_{H, \text{Network}} \sim 0.02\text{-}0.1 \text{ cm}^2/\text{V-s}$
- Junctions between tubes and bundles dominate conductivity

SWCNT Network Conductivity

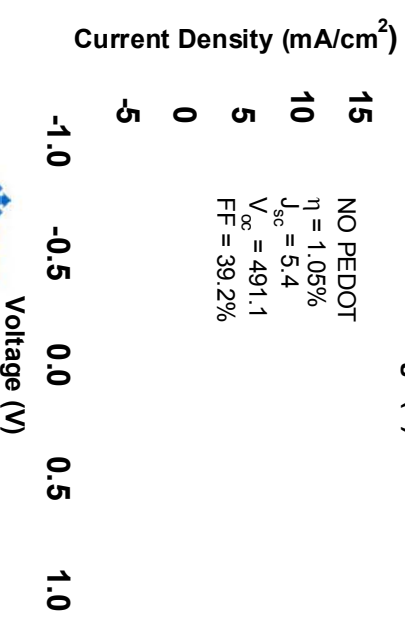
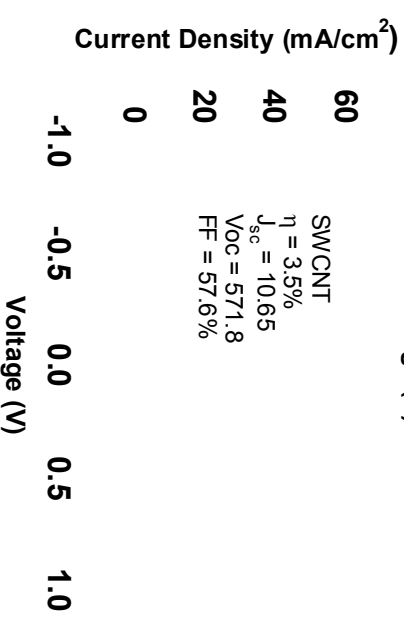
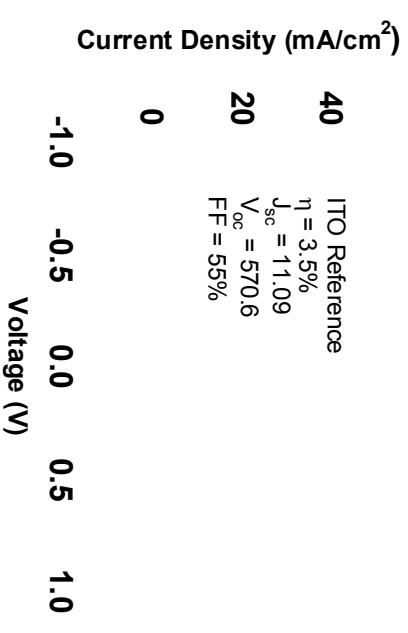
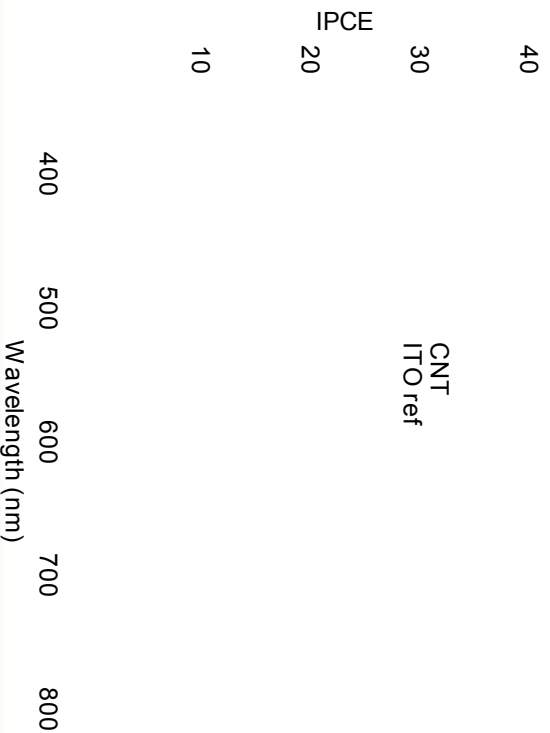


Absorption peaks at 650 and 950 are due to fundamental excitonic transitions of SWCNT

- Networks are soaked in HNO_3 after deposition
 - Network consolidation
 - Conductivity Improvement
 - $R_s = 60 \Omega/\text{sq}$
- Rinsing after acid
 - Promotes adhesion
 - Improves stability
 - R_s increases to $108 \Omega/\text{sq}$

Devices on NREL SWCNT Networks

- Ultrasonic spray deposition
- Several ~ 3% devices
- Thick active layers - spun at 200 rpm
- Reducing electrode roughness is key
- PEDOT can be eliminated



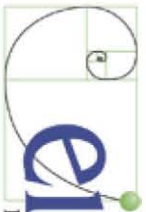
Conclusions

- SWCNT networks are the best hole-conducting TC available
 - Enables new device structures using “p” TC
- SWCNT is a good flexible TC
- Optoelectronic performance is improving
 - SWCNT processing, deposition, doping, m/s ratio
- Improve process compatibility for better device performance, new architectures (no PEDOT, invert)
- Device performance likely to improve for sprayed or printed active layers
- SWCNT networks could be a model for new TCs
 - If a completely black material works as a TC, then what else could we use??



Acknowledgements

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for materials and additional funding