OPTIMIZING CARBON NANOTUBE CONTACTS FOR USE IN ORGANIC PHOTOVOLTAICS

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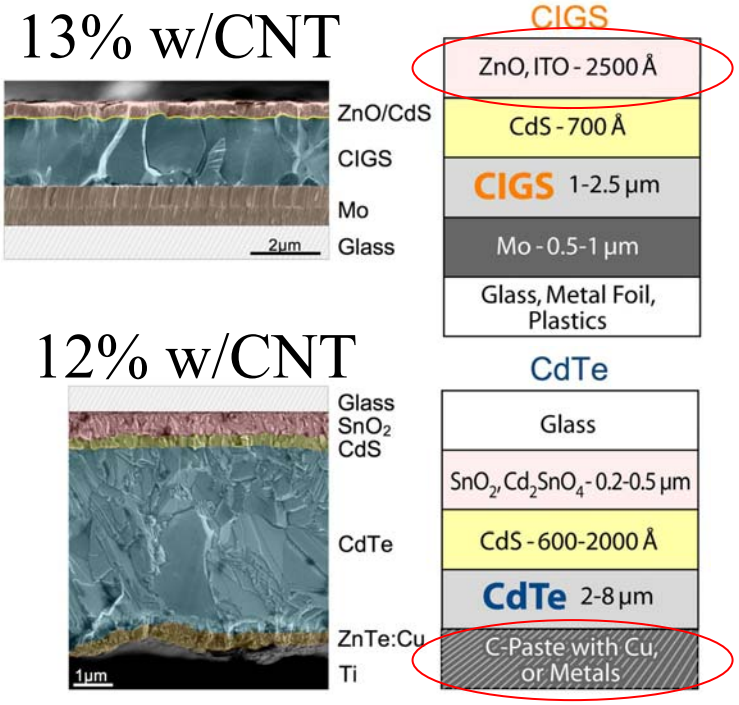
Transparent Contacts in PV

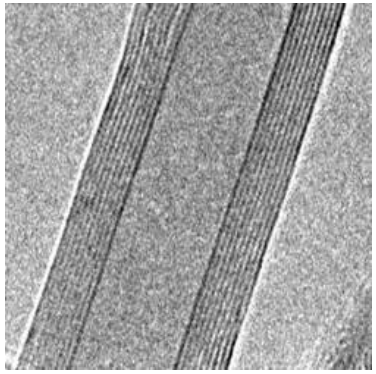
- Thin Film Devices
  - CdTe (16.5%) – TC sees 600°C
  - CIGS (20%) – TC must be grown at room T
- TCOs
  - ZnO:Al, SnO_2:F, In_2O_3:Sn, Cd_2SnO_4
- TCs must meet different requirements in each technology
- Successful demonstration of SWNT electrodes in thin film devices



www.nrel.gov/ncpv/thin_film/docs/wc4papernoufi__.doc
CIGS - Contreras, J.Phys.Chem. C, 14045, 2007;
CdTe - Barnes, APL, 243503, 2007

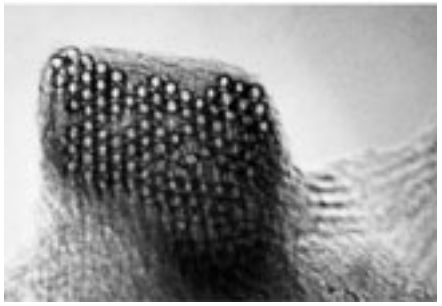
Carbon Nanotube Basics

Multi-wall tubes



Baughman, Science 287 2002

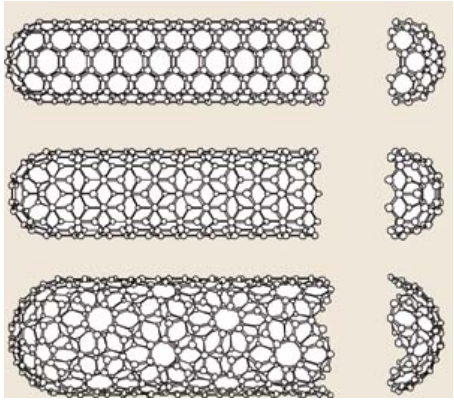
Single-wall bundle



Armchair (m)

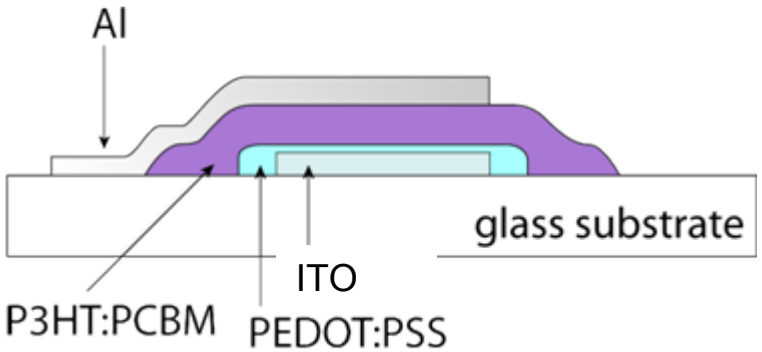
Zig-zag

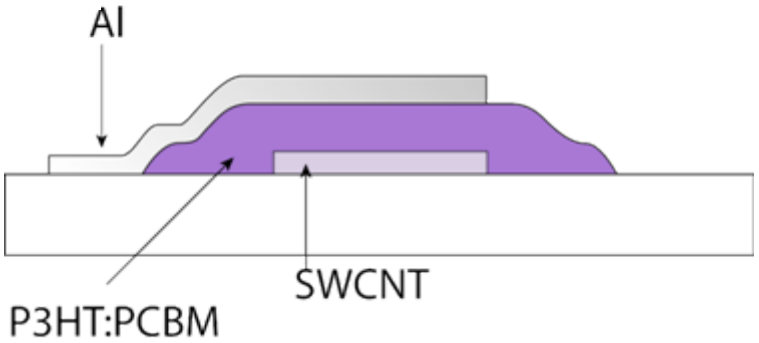
Chiral



- 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 ~ 300nm thick)

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

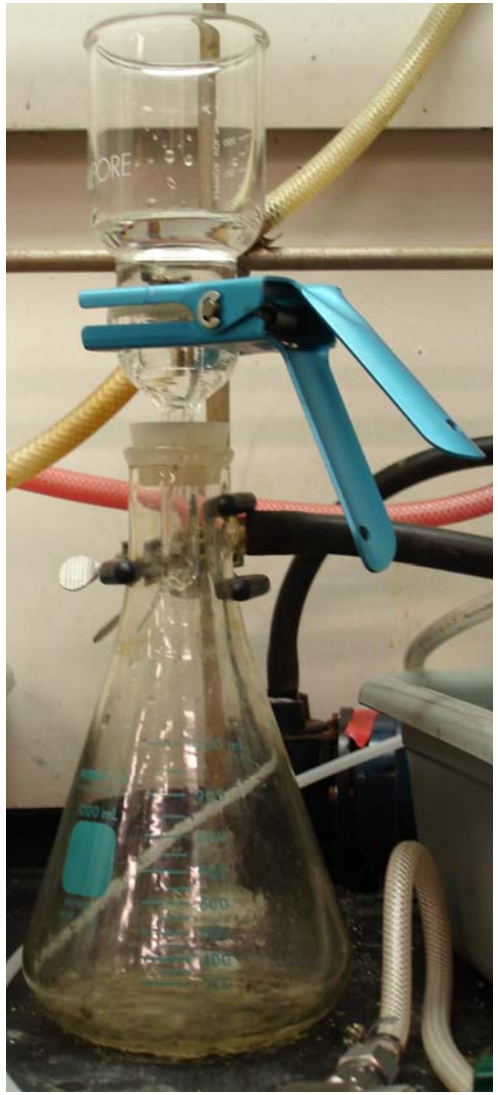
P3HT carries holes to the ITO side, PCBM transports electrons to Al

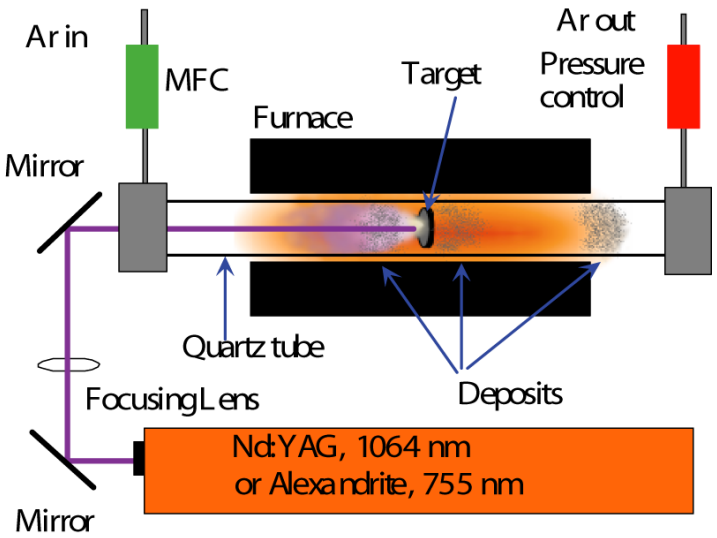
OPV Device Results:

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
- 1nm < d < 1.4 nm; all SWCNT
- PLV tubes are very long with low defect density (Raman D/G ~1/190)
- Films formed by vacuum filtration/ membrane transfer

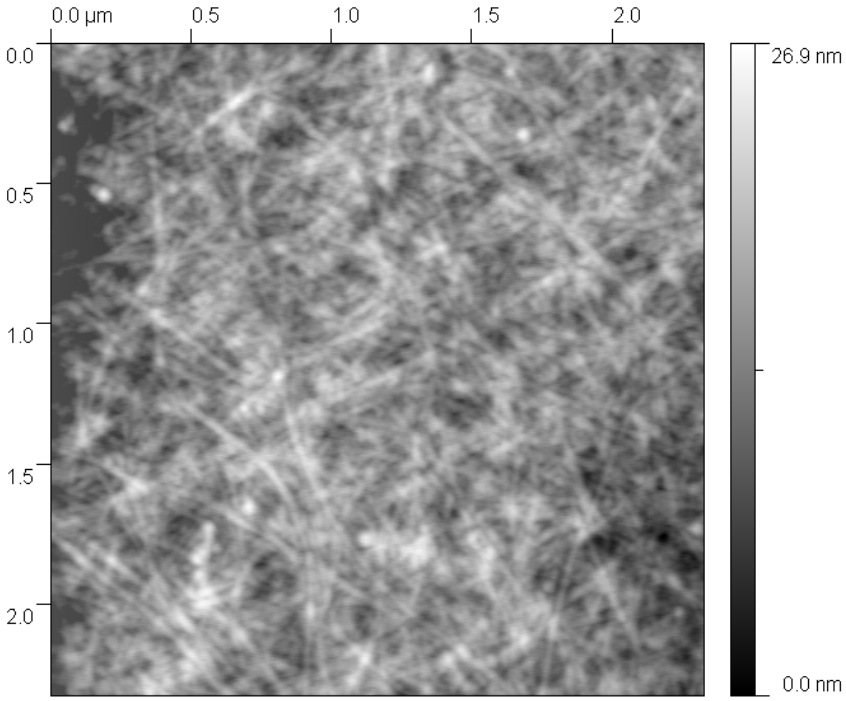




NREL Pulsed Laser Vaporization

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

Scalable Production: Ultra-sonic spray



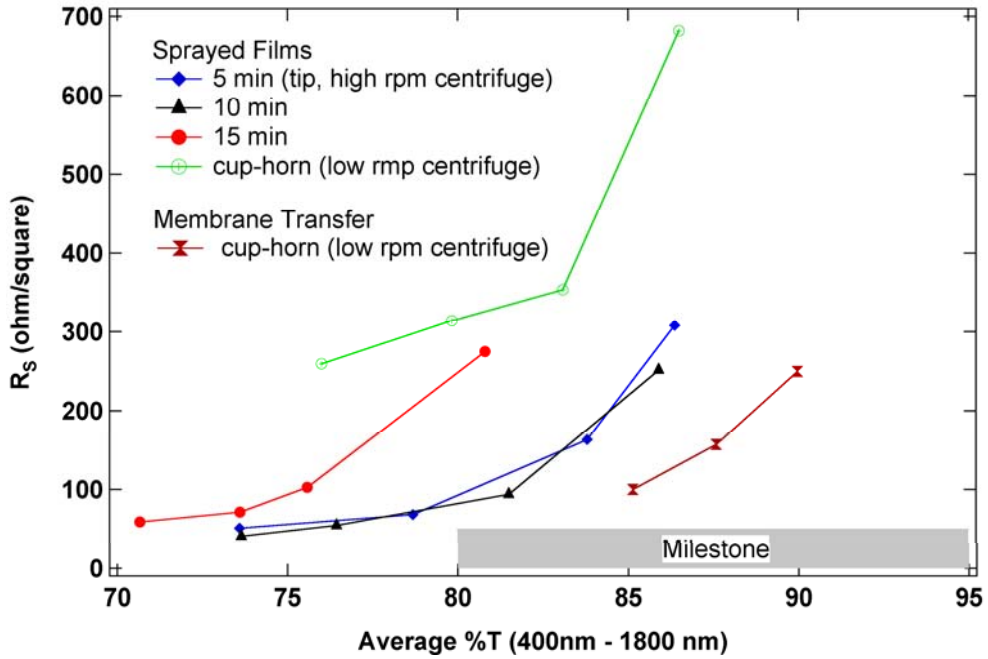
Metrics: Transparency, Conductivity, Stability

Parameter Matrix

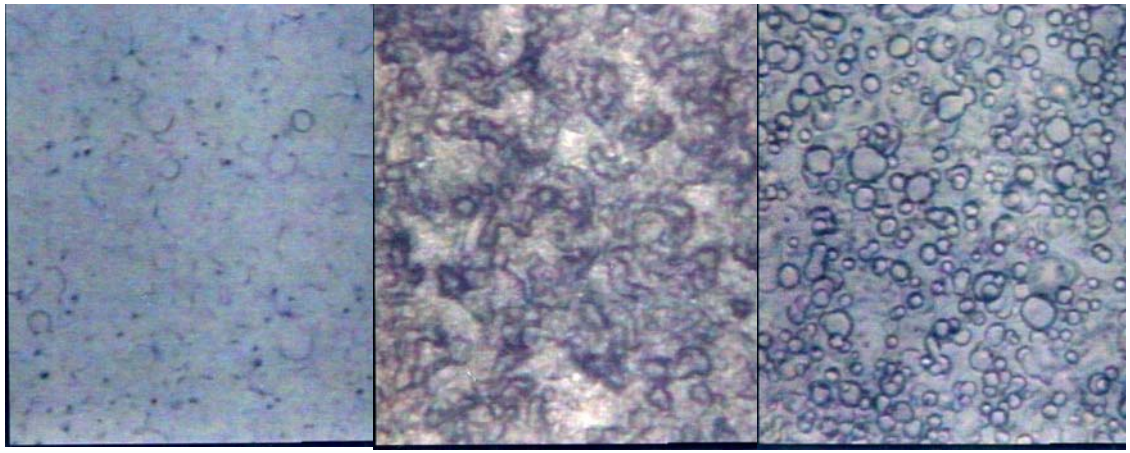
Purification: metals, amorphous C
Surfactant: SWCNT dispersion, bundle size
Sonication: SWCNT length, bundle size, defects
Post Processing: surfactant removal, doping
Surface Functionalization: wetting, drop formation

1 x 4 inch

Ink Formulation for Ultrasonic Spray

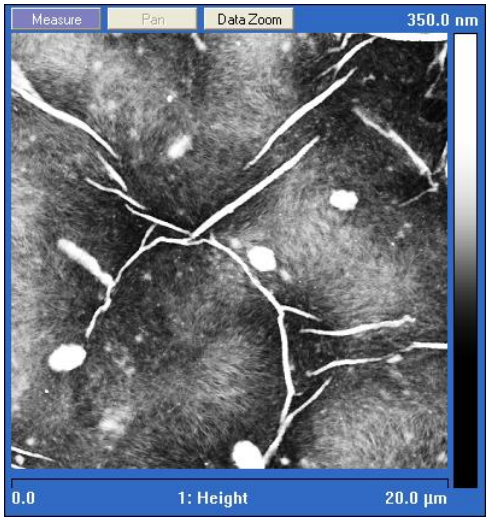


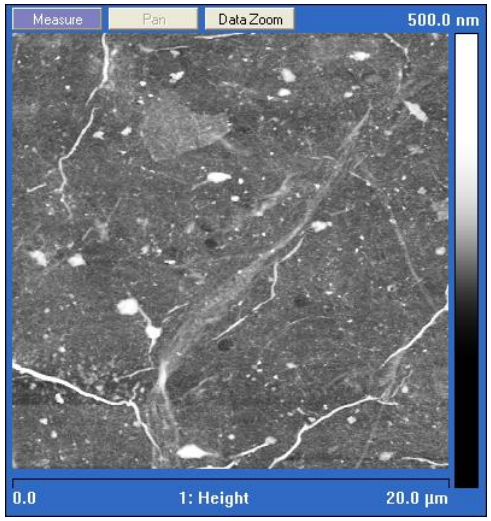
Best OK Bad



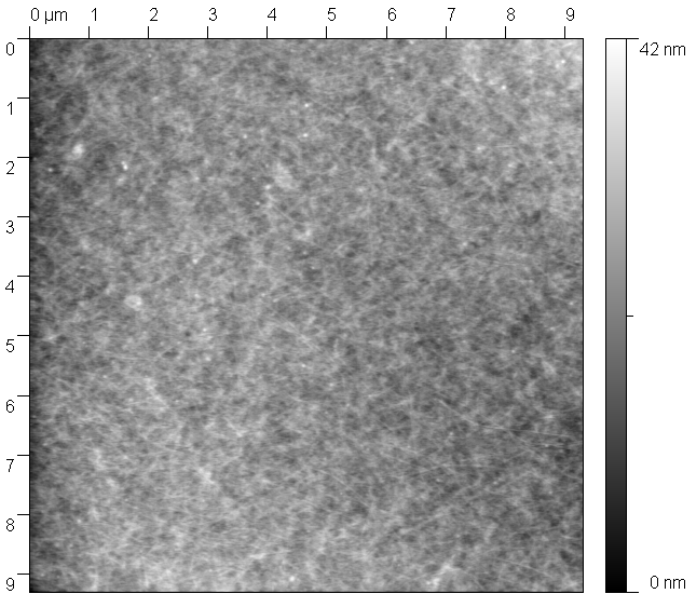
- Aqueous inks
- Ink sonication
- Tube purification/ starting material
- Surfactant choice is key
  - Morphology
  - Conductivity
  - Removal

Sprayed vs. Membrane Transferred





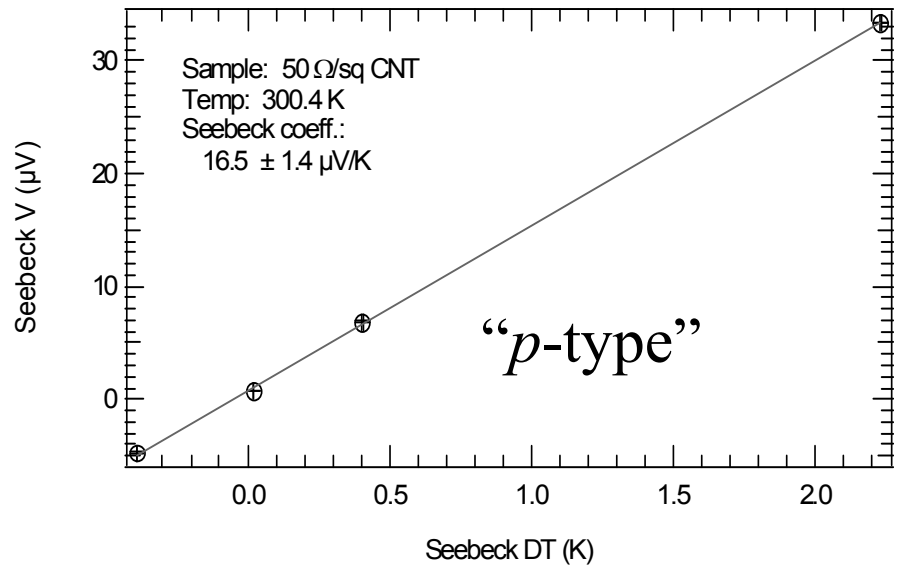
- Large scale roughness in membrane films
- Possible texturing from membrane
- Wrinkling

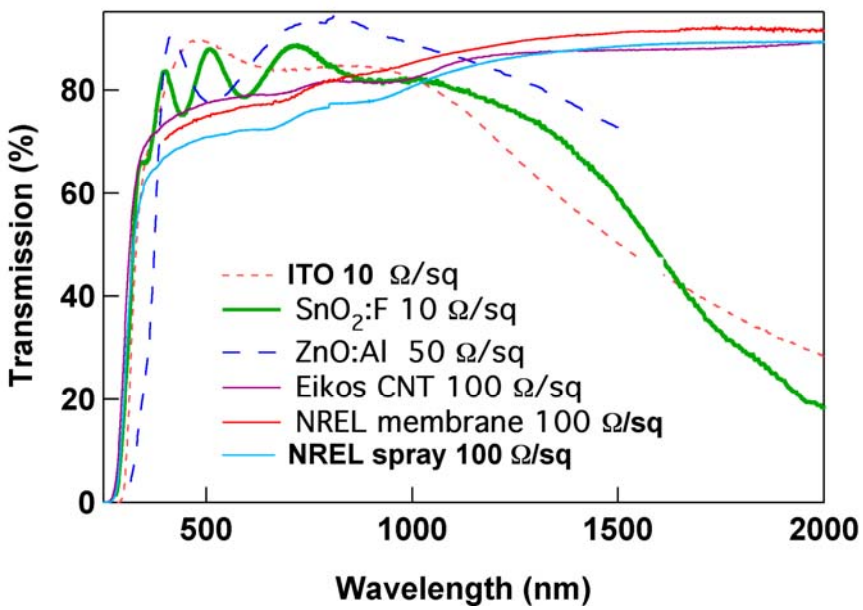


- Sprayed films are more uniform
- ~70 Ω/sq, 80% T (400-1500 nm)
- Smooth and featureless
  - Potential for fewer shorts in devices
  - Fewer apparent impurities

Compare TCOs with SWCNTs

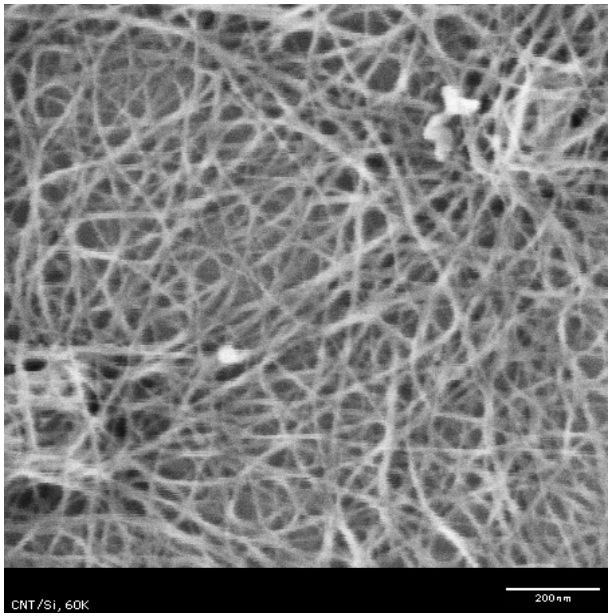
- Transparent SWCNT
  - Spaghetti-like network
  - ~50 nm thick
- Hole conducting

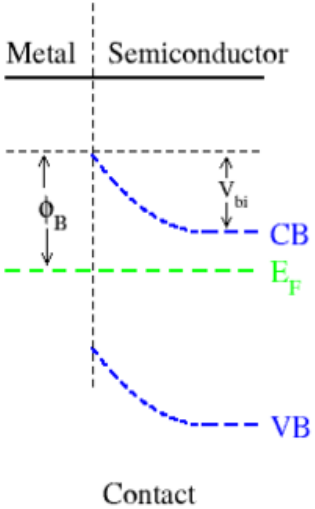




- Functional in solar cells (w/ performance drop)
- Need to improve R_s/T
  - Doping, separations,
  - improved deposition, purification processes

Conductivity in "Bulk" Networks





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

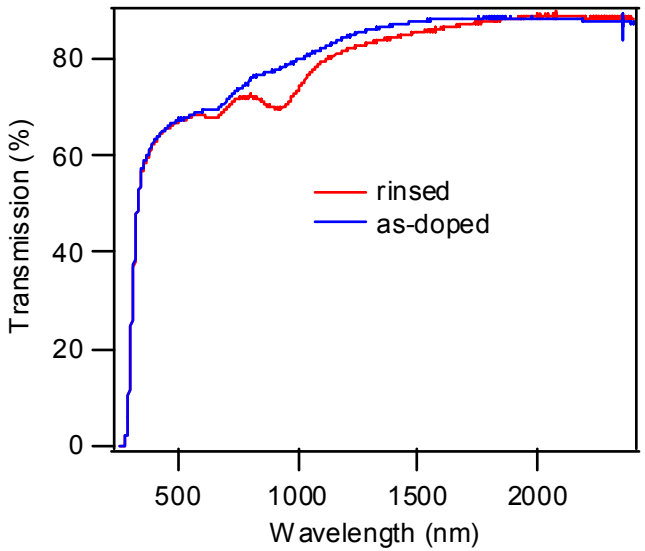
- Mixture of metallic (1/3) and semiconducting (2/3) tubes
- Tubes/bundles have high aspect ratio in "good" networks
- Measured "p" is low, but networks behave like degenerate semi
- Mobility of the network is very different from individual tubes

$\mu_{H,\ tube}$ ~ 1000-10000 $cm^2/V\text{-}s$

$\mu_{H,\ Network}$ ~ 0.02-0.1$cm^2/V\text{-}s$

Junctions between tubes and bundles dominate conductivity

SWCNT Network Conductivity

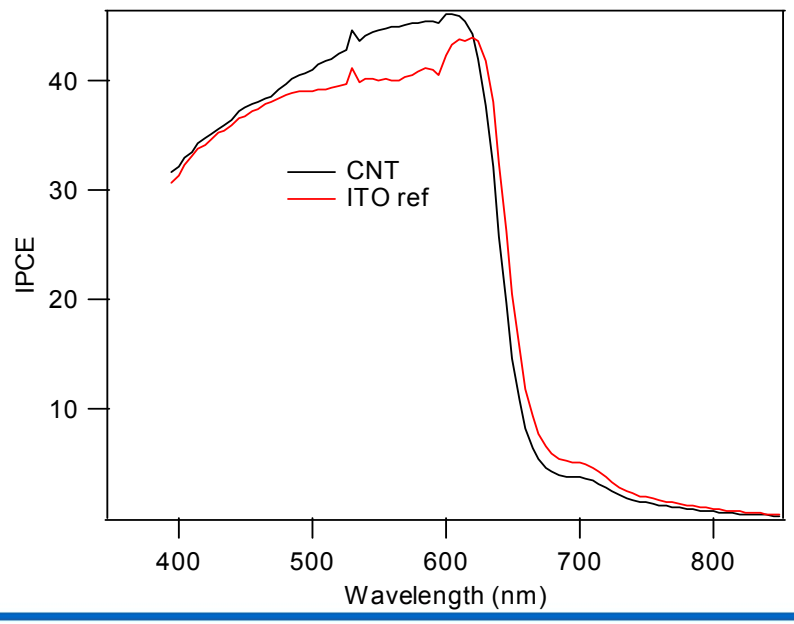


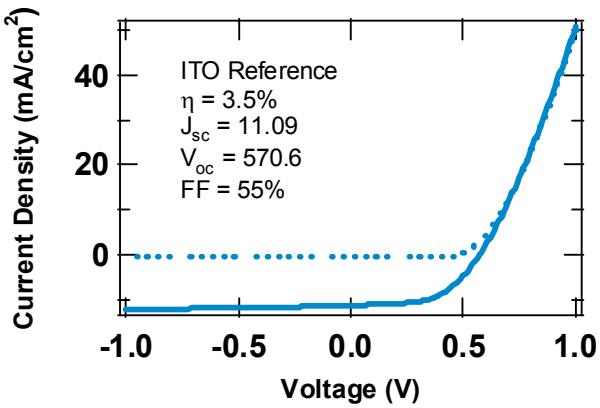
Absorption peaks at 650 and 950 are due to fundamental excitonic transitions of SWCNT

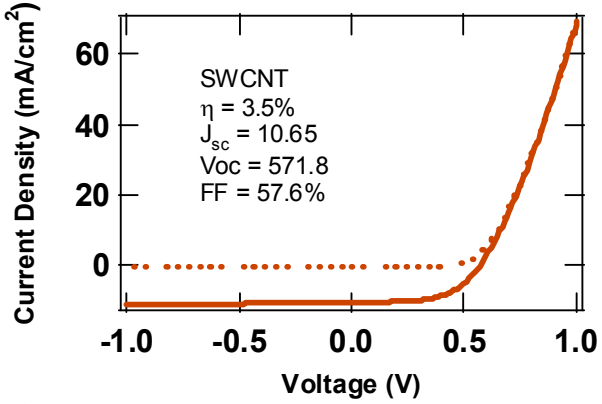
- Networks are soaked in HNO_3 after deposition
  - Network consolidation
  - Conductivity Improvement
  - R_s = 60 Ω/sq
- Rinsing after acid
  - Promotes adhesion
  - Improves stability
  - R_s increases to 108 Ω/sq

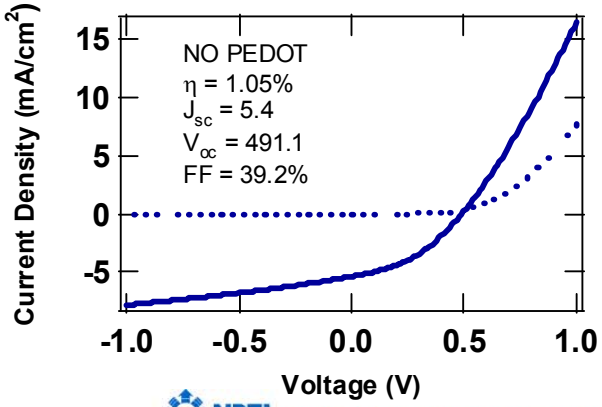
Devices on NREL SWCNT Networks

- 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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