Some of our work

Baratunde Cola

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School of Materials Science and Engineering
Institute for Electronics and Nanotechnology
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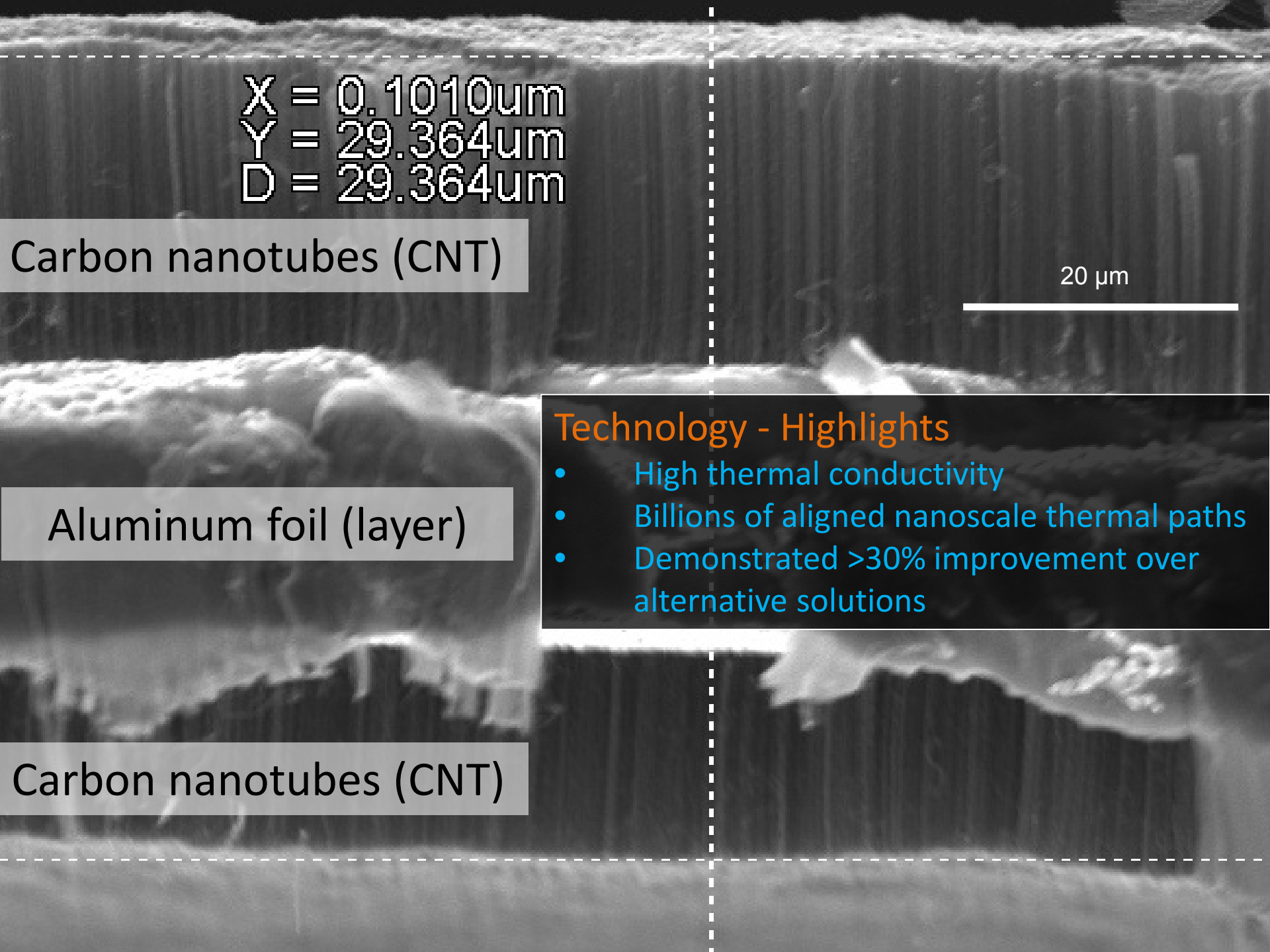
Sponsors: DARPA, NSF, Georgia Research Alliance, Samsung

Students: **P. Pour Shahid Saeed Abadi**, **T.L. Bougher**, **J. Taphouse**, **V. Singh, M.K. Smith**

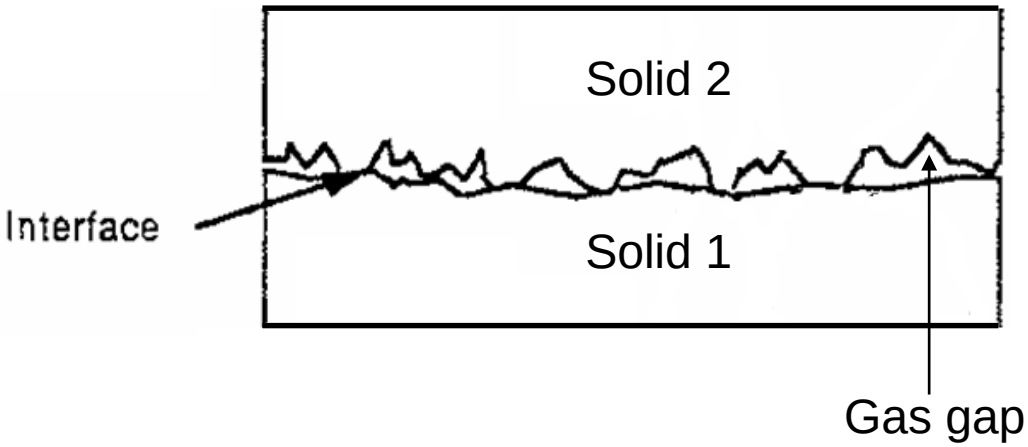
10 May 2017
National Science Board Meeting



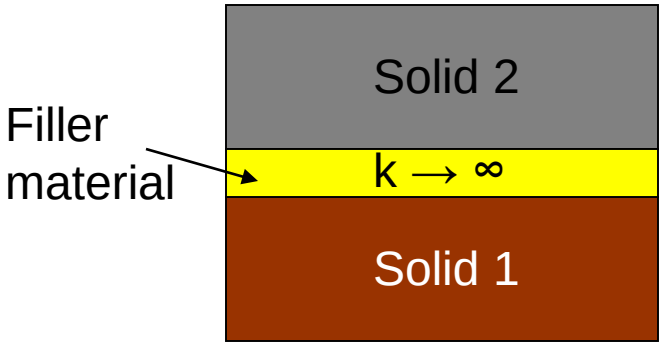
Technology - Highlights

- High thermal conductivity
- Billions of aligned nanoscale thermal paths
- Demonstrated >30% improvement over alternative solutions

Real interface



'Ideal' interface



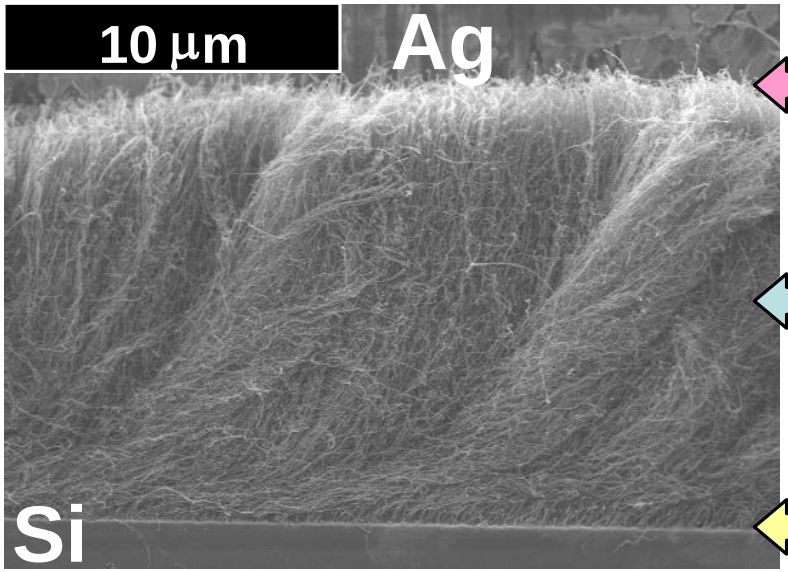
Characteristics desired for thermal interface materials

- High thermal conductivity
- High conformability
- Chemically and mechanically robust in diverse environments
- Major challenge: *soft materials with high thermal conductivity are rare in nature*

Resolving CNT Interfaces: One-Sided

- Resolution enabled by photoacoustic thermal measurement

B.A. Cola et al., *J. Appl. Phys.* **101**, 054313 (2007)

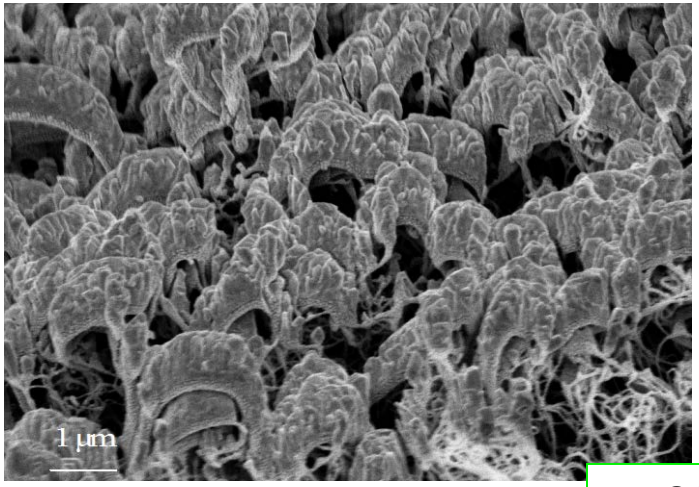


$$R_{\text{Ag-CNT}} = 14.0\,(12.2 - 14.8)\ \text{mm}^2\text{K/W}$$

$$R_{\text{CNT layer}} < 0.1\ \text{mm}^2\text{K/W}$$

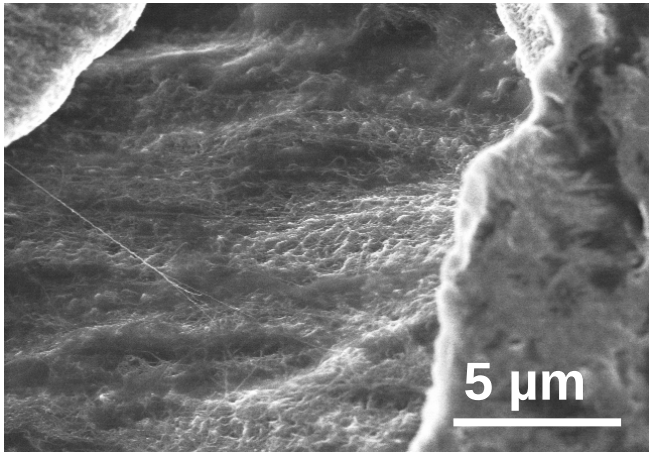
$$R_{\text{Si-CNT}} = 1.7\,(1.0 - 3.4)\ \text{mm}^2\text{K/W}$$

Gold coated CNTs



R. Cross et al., *Nanotechnology*, (2010)

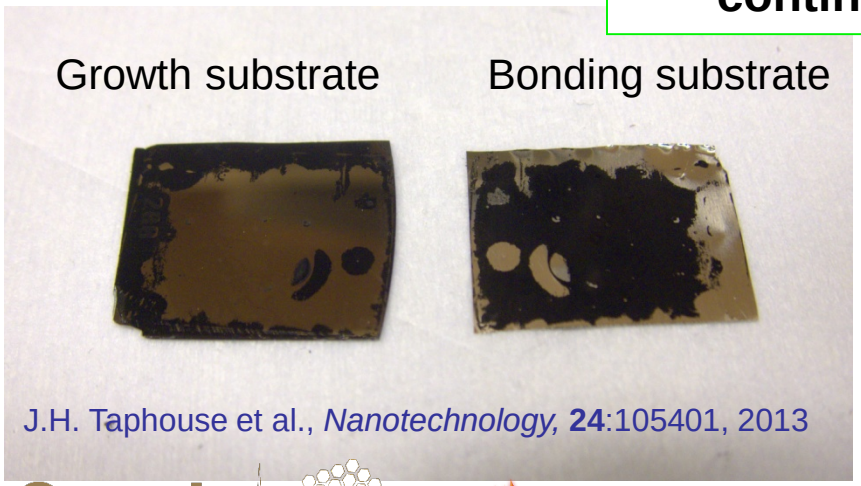
Wax coated CNTs



mmer Heat Transfer Conference 2008

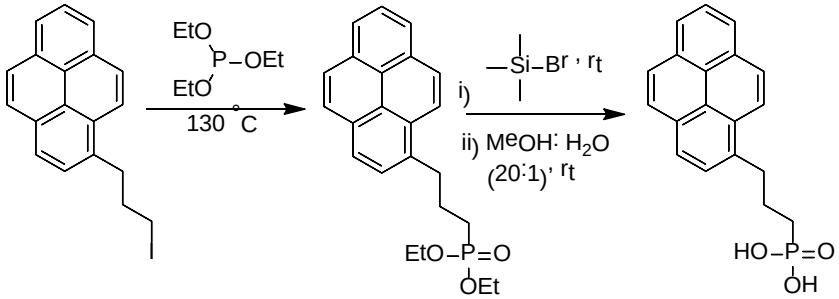
~100% resistance reductions with each approach, but reliability and scalability continues to improve

Sprayed on Polymer Bo



J.H. Taphouse et al., *Nanotechnology,* **24**:105401, 2013

er Surface Modifiers

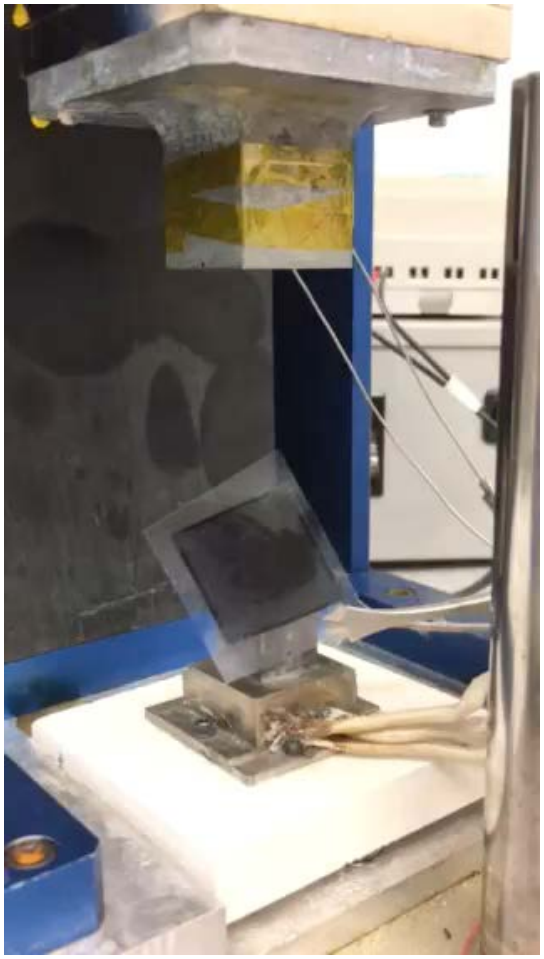


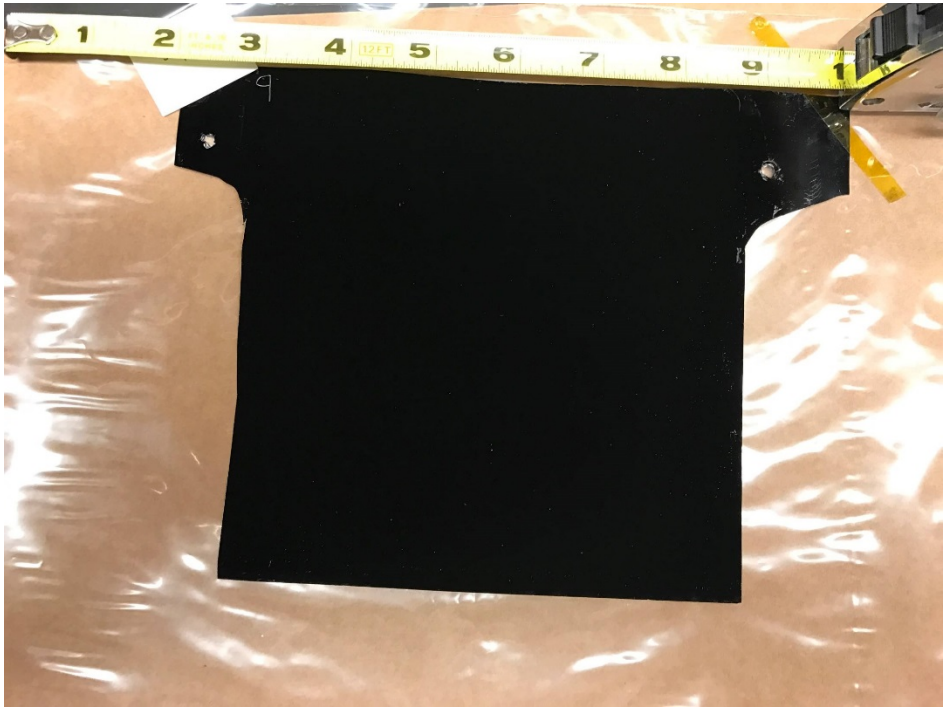
J.H. Taphouse et al., *Advanced Functional Materials*, 2014

Collaboration with organic chemist Dr. Seth Marder (GT)

CARBICE

CORPORATION

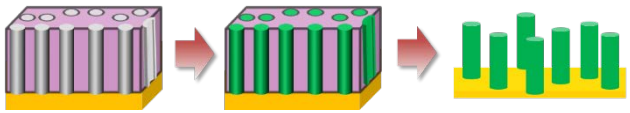


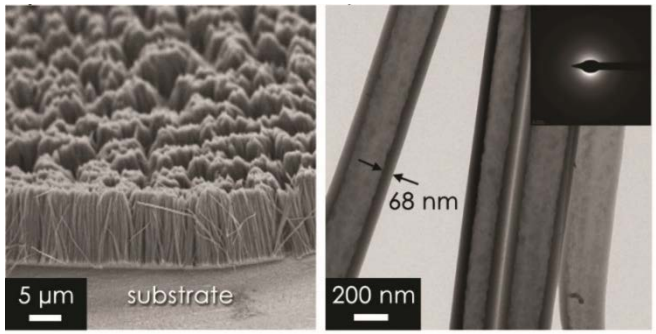


Funding to date:
>$2 million grants
$1.4 million in angel and VC funds

First Thermally Conductive Amorphous Polymer

NEST RESEARCH



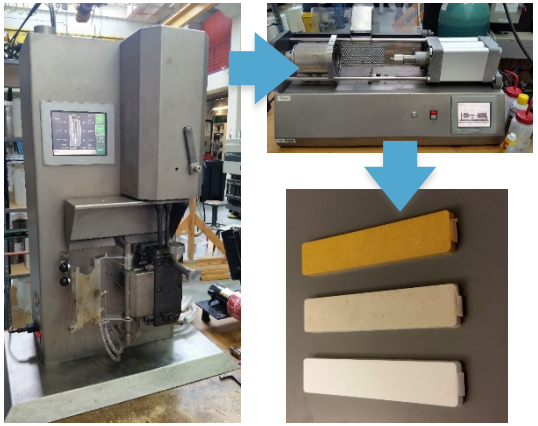


V. Singh, et al. *Nat Nanotecnol (5)*, 2014

National Science Foundation
WHERE DISCOVERIES BEGIN

SAMSUNG

TCPOLY PROTOYPE



NSF CORPS NSF Innovation Corps

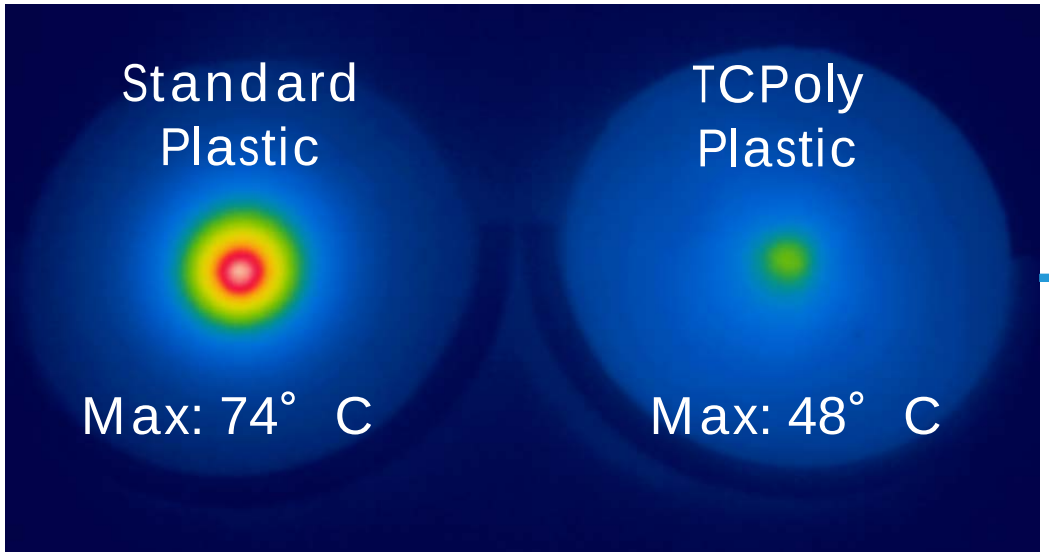
Georgia Research Alliance

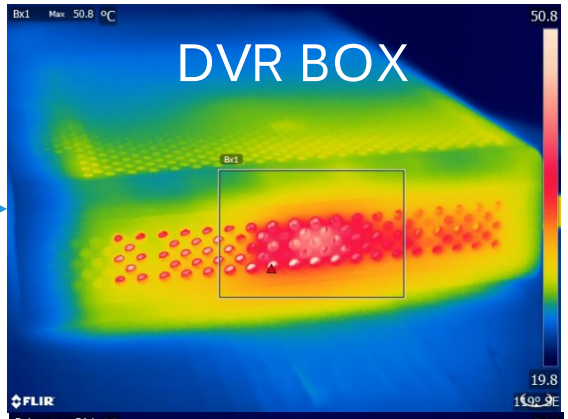
SCALE

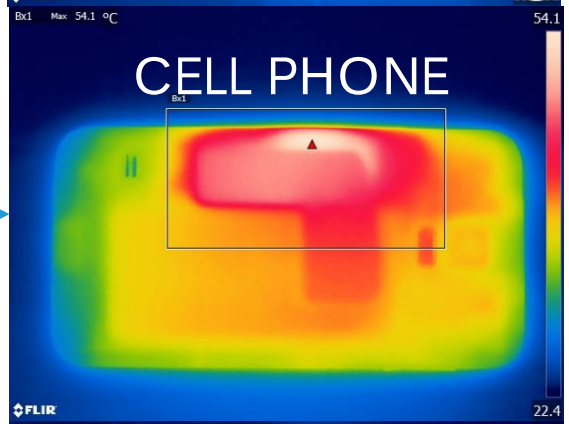
SBIR · STTR
America's Seed Fund

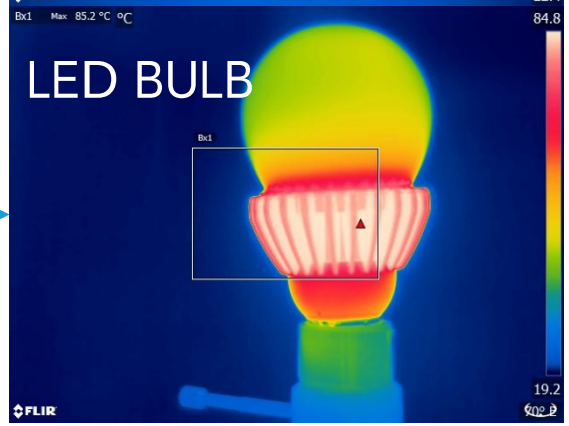
PLASTICS FOR COOLER ELECTRONICS

TCPOLY

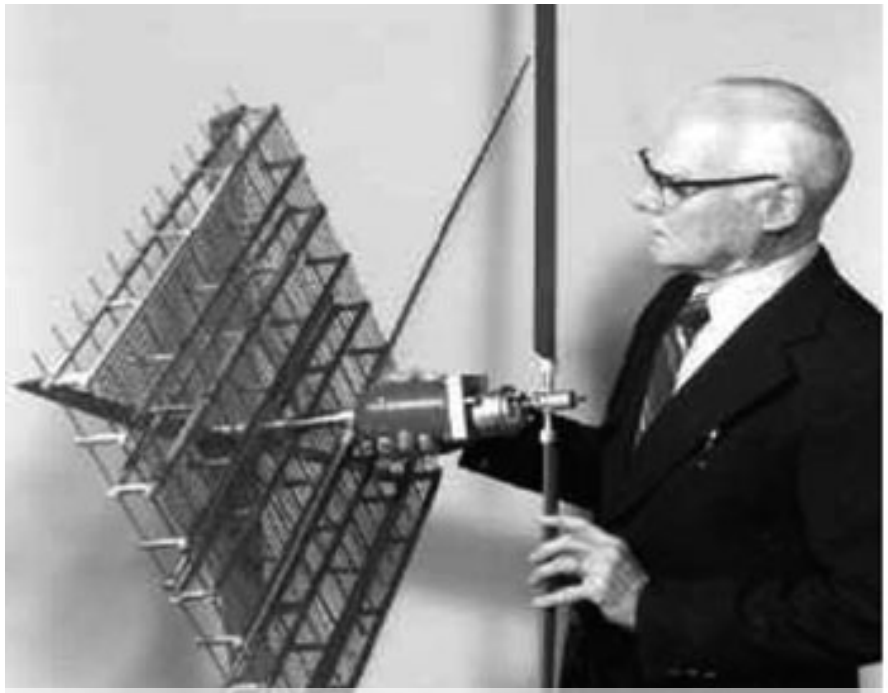




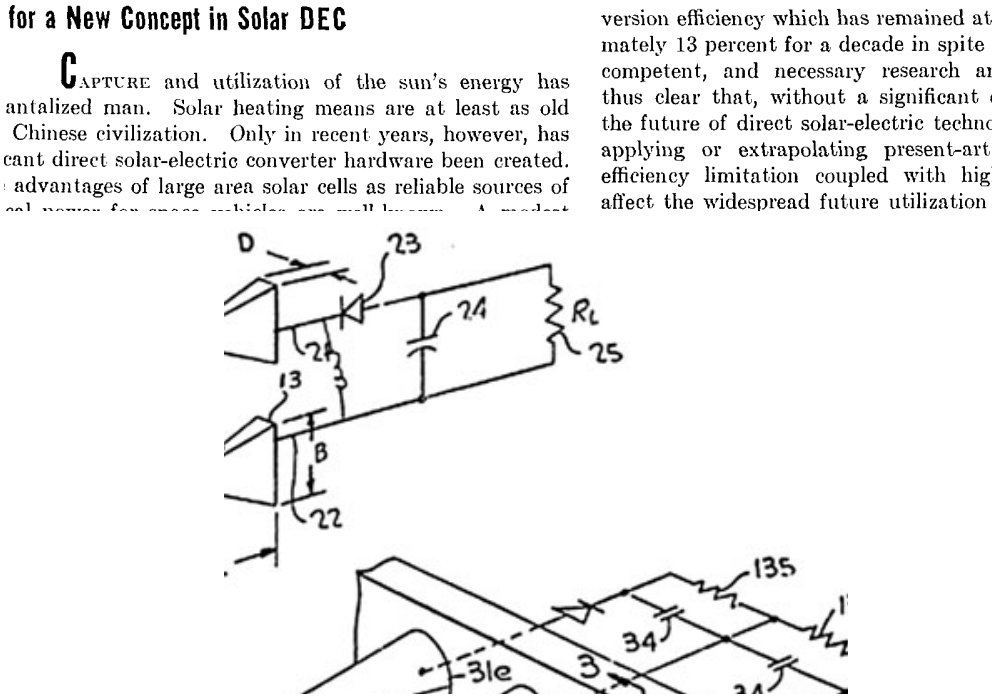




Rectifying Antenna or ‘Rectenna’



Microwave rectenna
(born 1963, Raytheon and Purdue)



for a New Concept in Solar DEC

CAPTURE and utilization of the sun's energy has antalized man. Solar heating means are at least as old Chinese civilization. Only in recent years, however, has cant direct solar-electric converter hardware been created. advantages of large area solar cells as reliable sources of

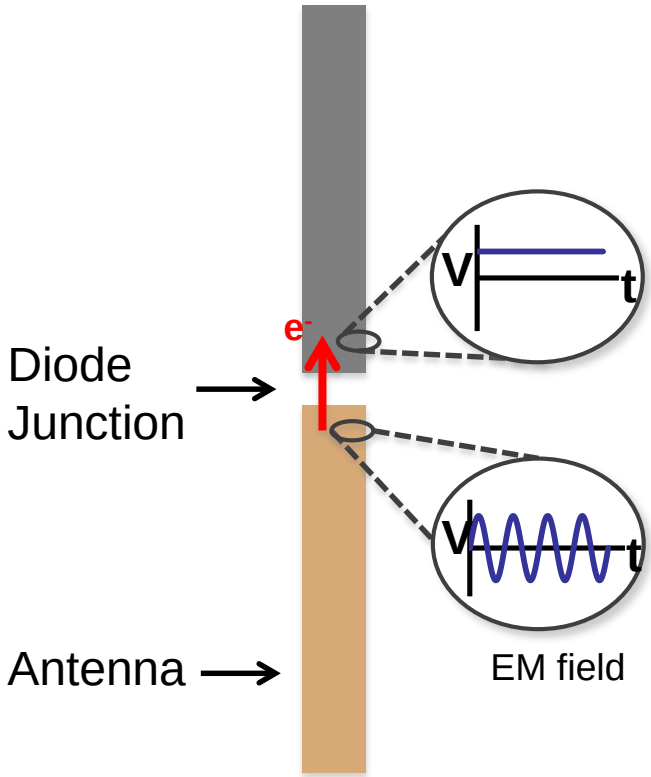
version efficiency which has remained at mately 13 percent for a decade in spite competent, and necessary research ar thus clear that, without a significant the future of direct solar-electric techno applying or extrapolating present-art efficiency limitation coupled with hig affect the widespread future utilization

Solar rectenna
(proposed 1972)

Demonstrated efficiencies > 80%

***Predicted* efficiencies > 80%**

Rectification Physics (Classical)



Cutoff frequency

$$f_c = \frac{R_A + R_D}{2\pi R_A R_D C_D}$$

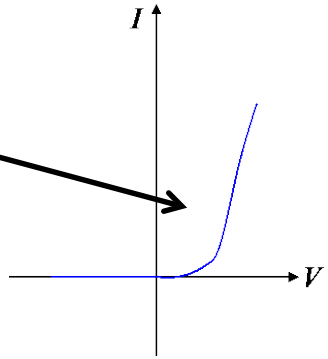
$$C_D = \varepsilon_0 \varepsilon . A/d$$

Diode resistance

$$R = 1/(\partial I/\partial V)$$

Diode responsivity

$$\beta = 1/2\,(\partial^2 I/\partial V^2)/(\partial I/\partial V)$$

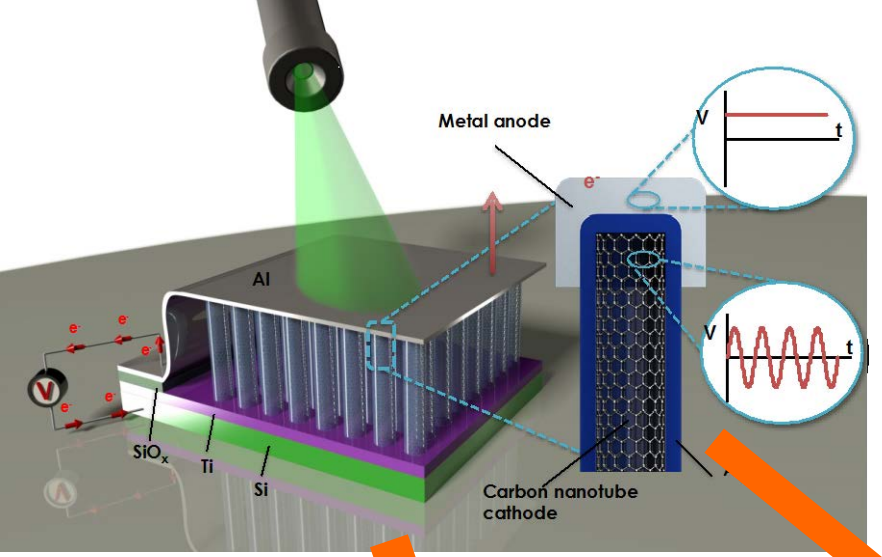


Rectenna voltage and power output

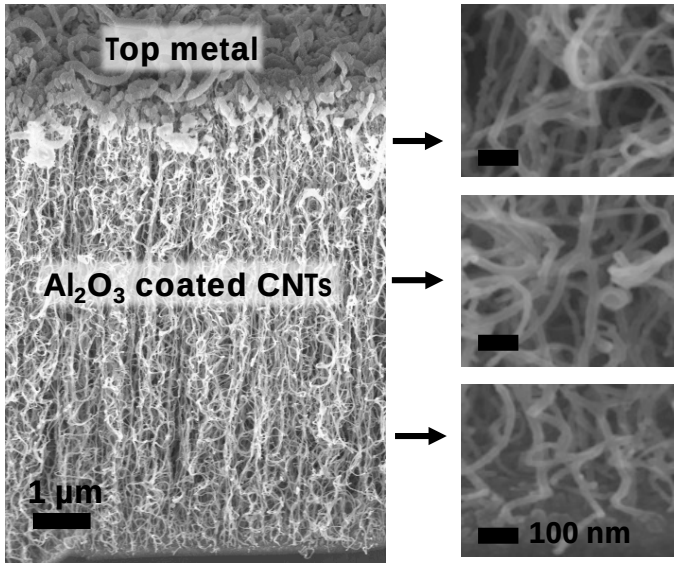
$$V_D = -1/2\,\beta V_{opt}^2$$

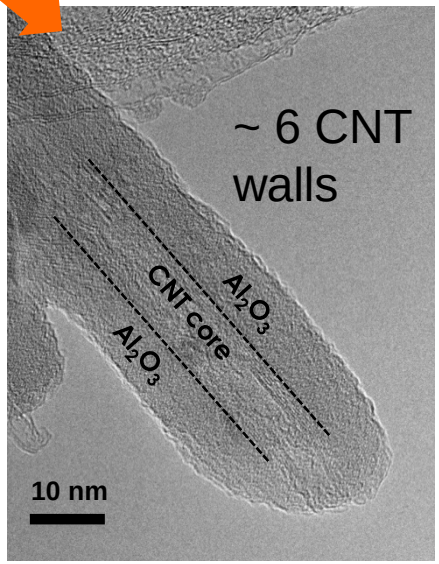
$$P_{out} = -\beta^2 V_{opt}^4/16R$$

MWCNT Rectenna: Structural Detail

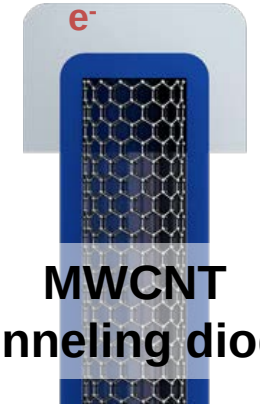


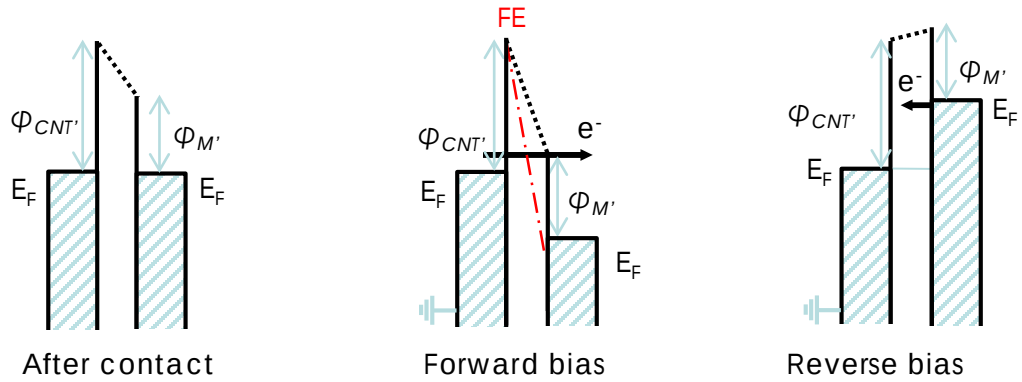
- 8 nm conformal alumina coating
- CNT tip field enhancement
- ~ 10 nm junction diameter (C~1 aF)
- Ca/Al low work function top contact (semi-transparent, ~10% transmission)



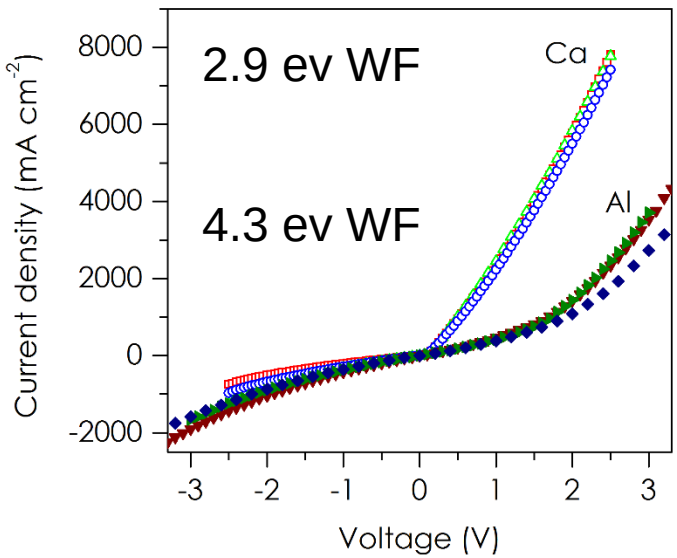


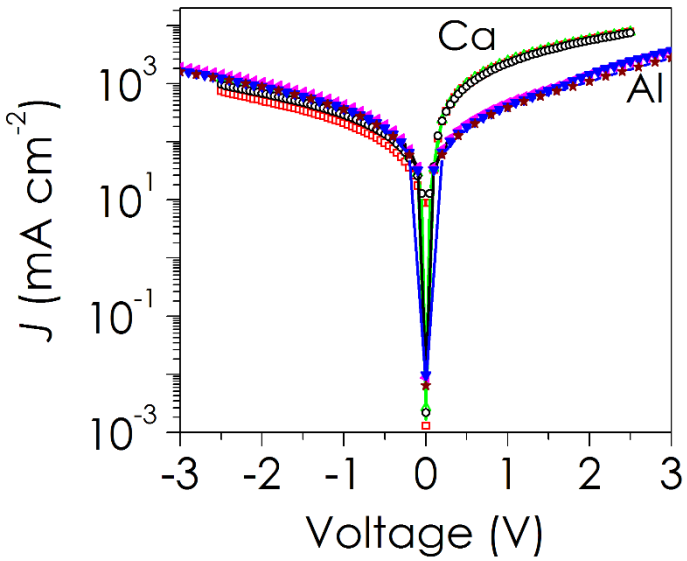
How the Tunneling Diode Works



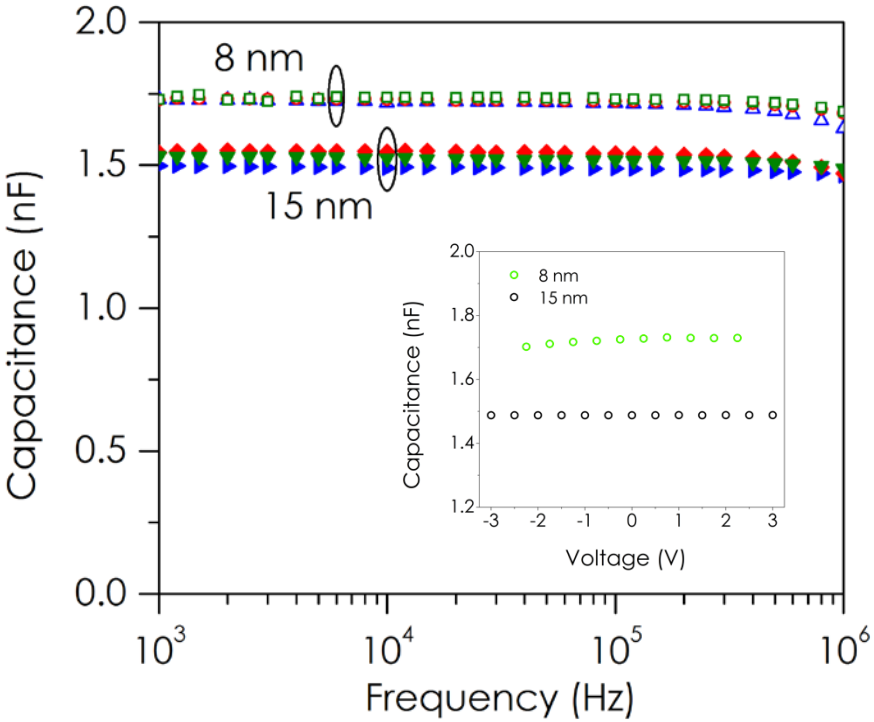


~ 5 ev MWCNT work function





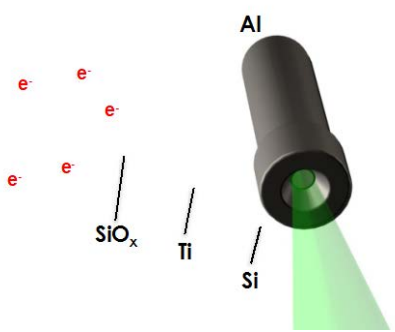
Device Capacitance

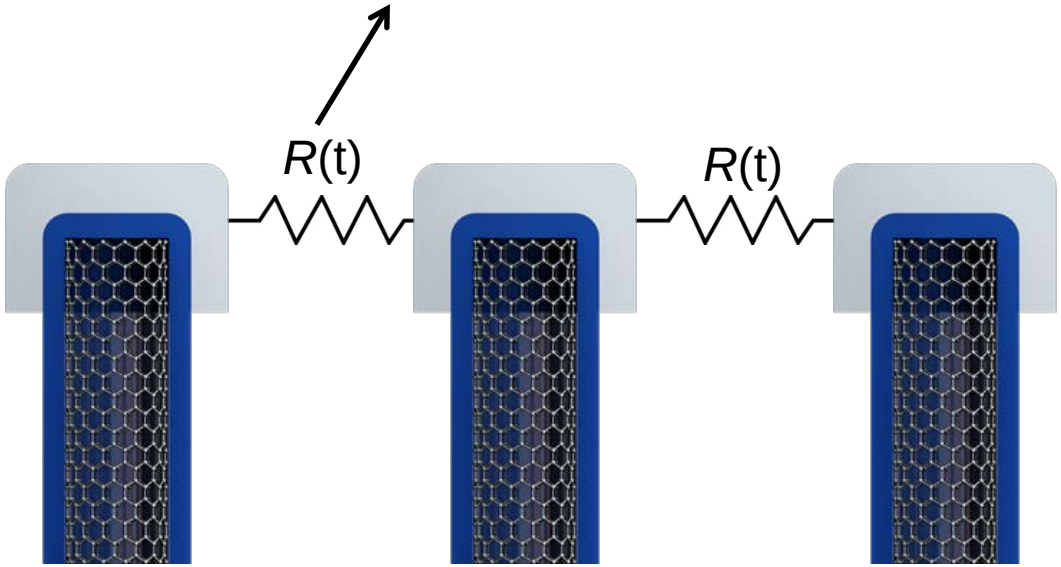


Length and time scale for rectification cutoff frequency is different from length and time scale of device operation!

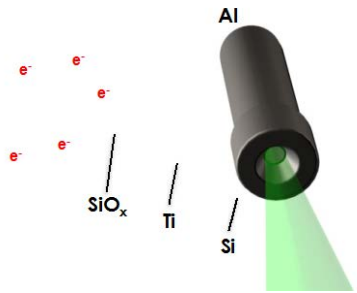
Fermi velocity < 10^6 m/s, so

***R*(t≈10^{-15} s) = ∞**





Impedance Matching



Poor impedance matching in a single junction is compensated by larger number of junctions, which allows power production.

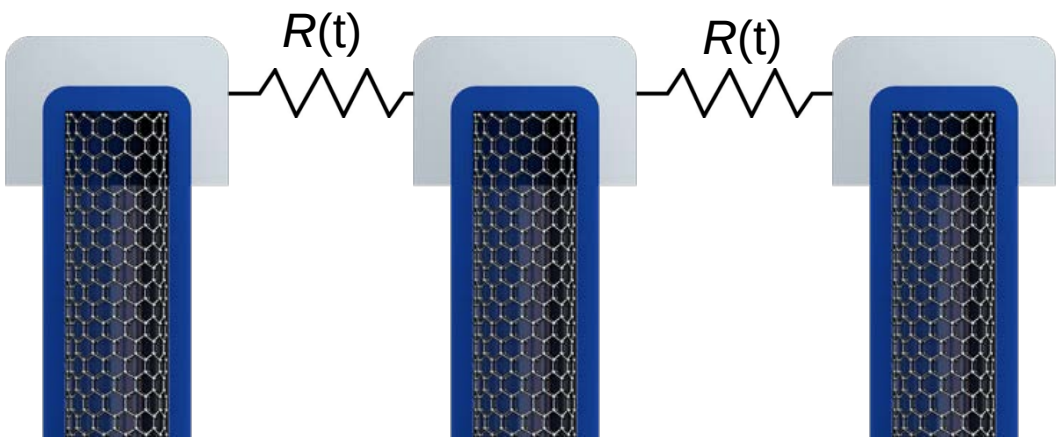
Collective antenna effects reduce coupling resistance to single CNT antenna.

Phys. Rev. B 87, 161401(R), 2013

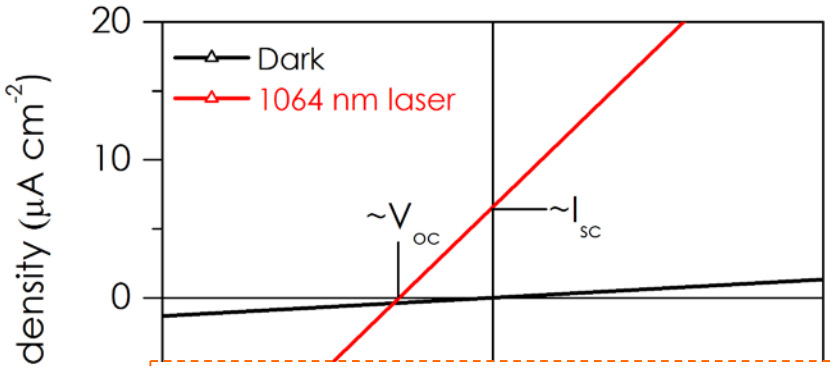
Collective Antenna Effects in the Terahertz and Infrared Response of Highly Aligned Carbon Nanotube Arrays

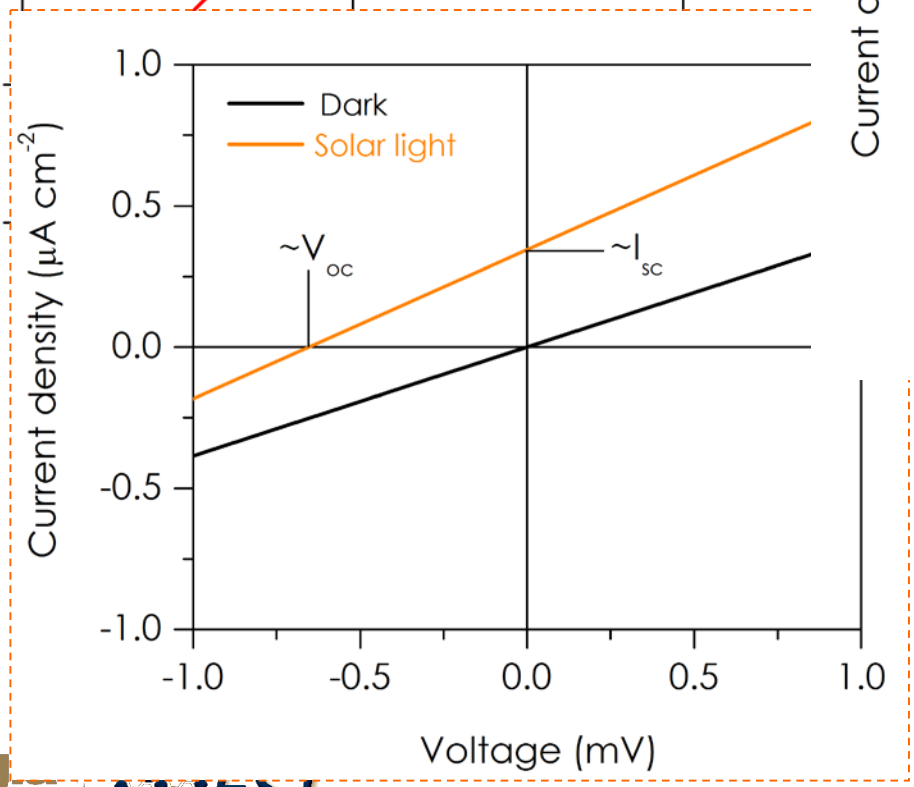
L. Ren,[1] Q. Zhang,[1] C. L. Pint,[2,3] A. K. Wójcik,[4] M. Bunney, Jr.,[5,6] T. Arikawa,[1] I. Kawayama,[7] M. Tonouchi,[7] R. H. Hauge,[2] A. A. Belyanin,[4] and J. Kono[1,8,*]

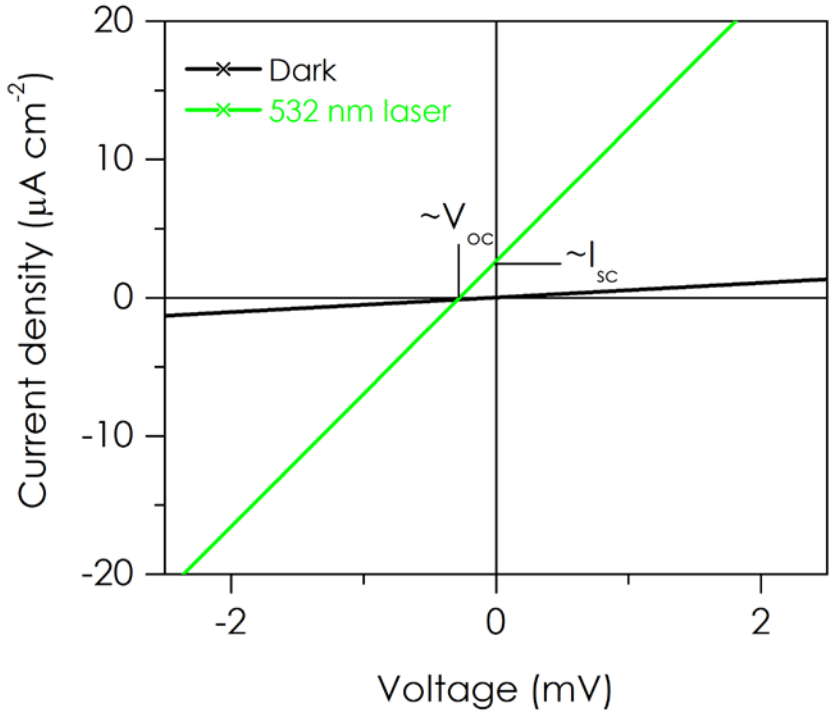
Collective CNT antenna array – approximately in phase



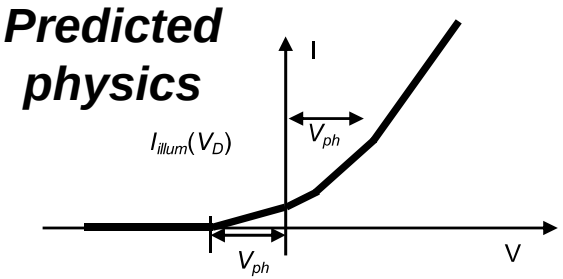
Rectification Photoresponse







Predicted physics



J. Phys. D: Appl. Phys. **46** (2013) 135106