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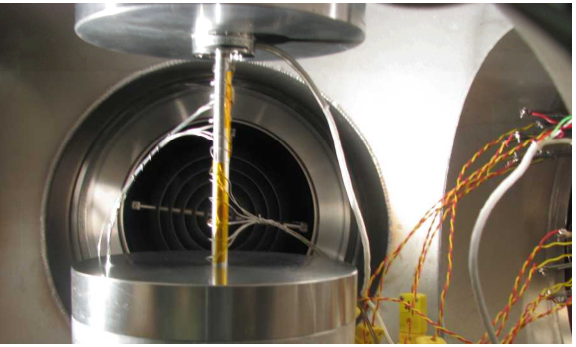

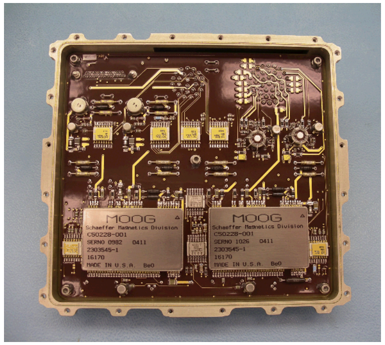

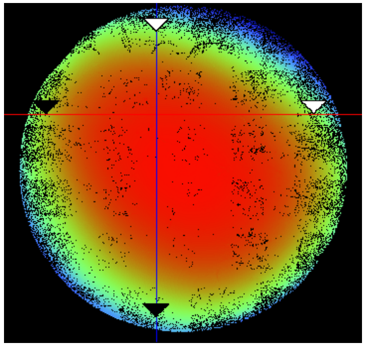

Effect of Gamma-Ray Irradiation on the Thermal Contact Conductance of Carbon Nanotube Thermal Interface Materials

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11/18/2013

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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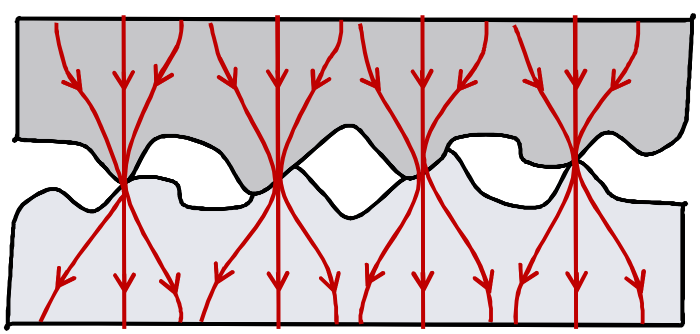
Thermal Contact Resistance

- For interfaces in contact, the real area of contact is typically 2 to 6 orders of magnitude less than the apparent area of contact $\frac{A_r}{A} = \frac{P}{H}$

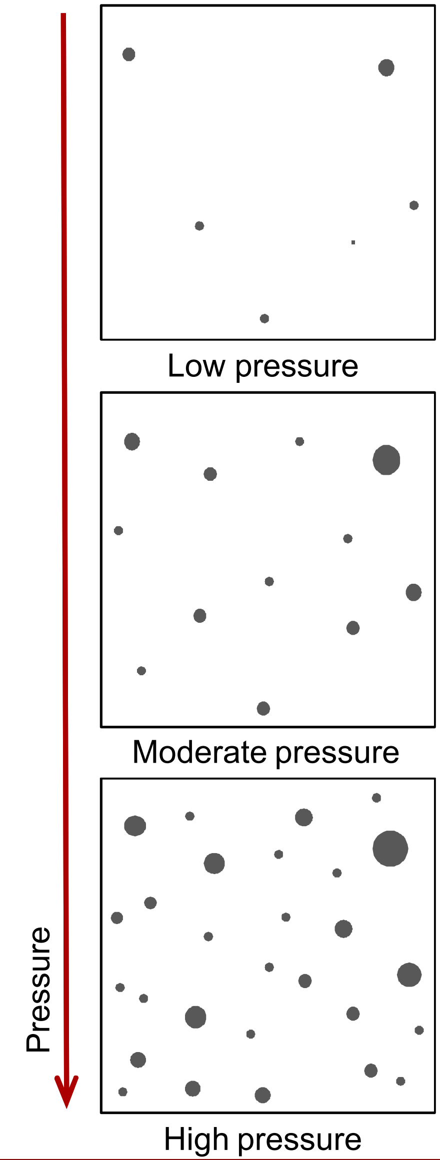
- In vacuum, thermal contact resistance (TCR) of a Gaussian surface is given by

$$R = 0.88 \frac{\sigma}{km} \left(\frac{H}{P} \right)^{0.94} = aP^b$$

- For systems with multiple interfaces, TCR can consume a significant part of the thermal budget

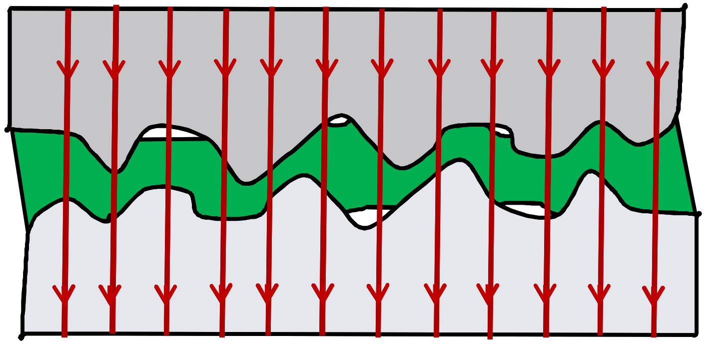


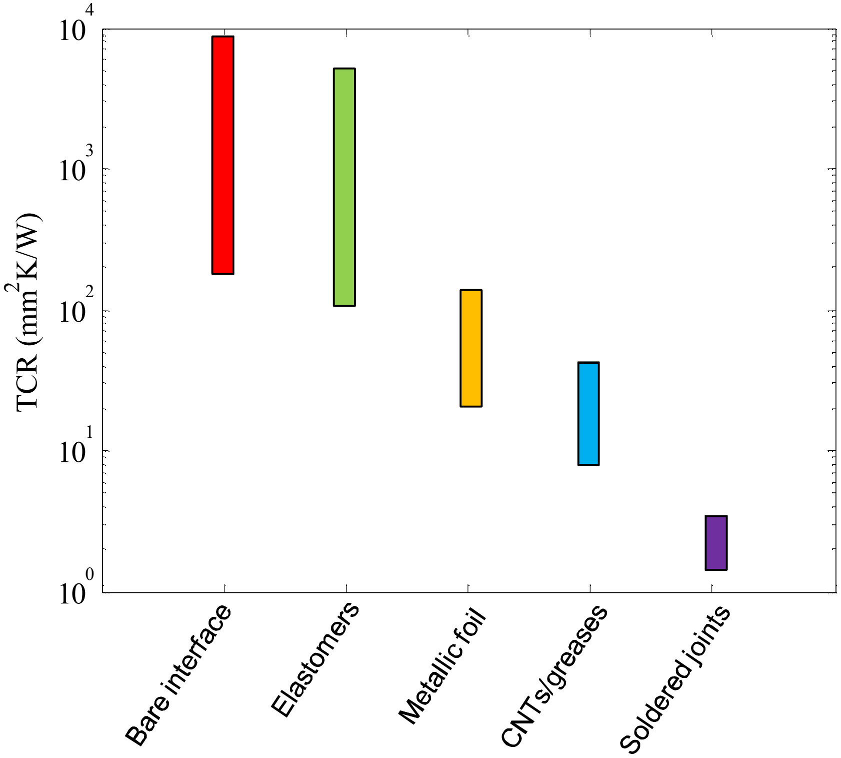
A	Apparent contact area
A_r	Real contact area
a,b	Constants
H	Hardness
k	Thermal conductivity
m	Asperity slope
P	Contact pressure
R	Contact resistance
σ	Surface roughness



Thermal Interface Materials

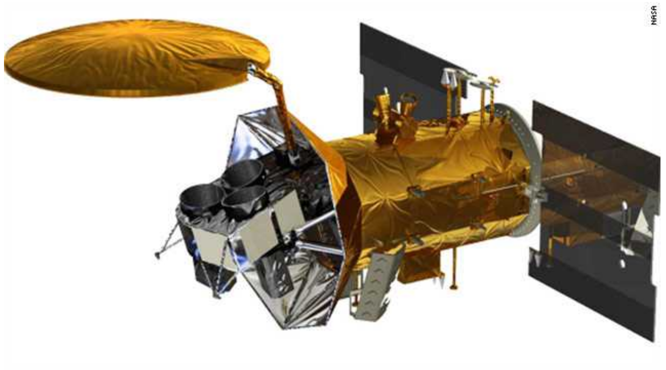
- Thermal interface materials (TIMs) provide a means of decreasing TCR by filling the gaps between asperity contacts
  - Thermal greases
  - Metallic foils
  - Carbon nanotube (CNT) materials
  - Elastomeric materials





Satellite Systems

- Special considerations are required for TIMs used in satellites
  - Low outgassing (NASA standards)
  - Lightweight
- Space systems are exposed to a wide array of radiation sources
  - UV
  - X-ray
  - Charged particles
  - γ-ray



NASA Aquarius satellite [1]

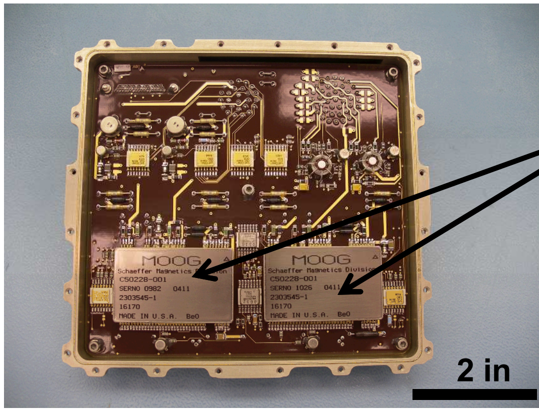
Absorbed and reflected by outer materials (UV, X-ray, charged particles)

γ-ray:
Experience little attenuation
Easily reach and pass through all components
Doses as high as 10 Mrad /yr [2]
Interactions with TIMs are important

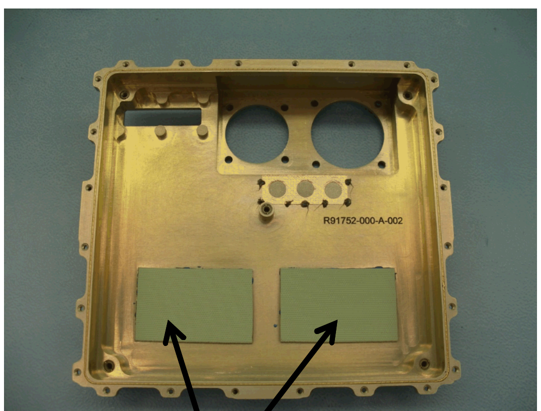
[1] CNN Wire Staff, NASA launches satellite for critical mapping mission, June 10, 2011.
[2] R. Akau et al., 2012, Nexus Test Report for Thermal and Mechanical Study of Silver-Teflon Tape for Space Applications, SNL, Albuquerque.

TIMS in Satellite Systems

Control electronics box assembly

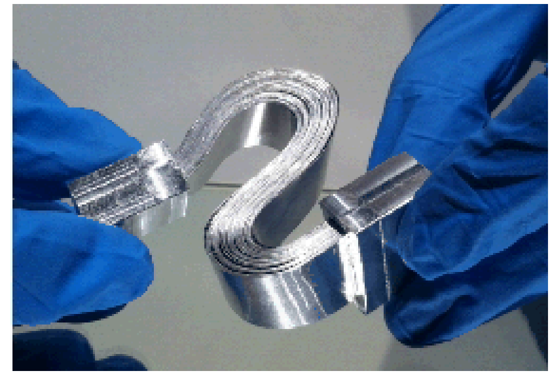


Power converters
4 W dissipated

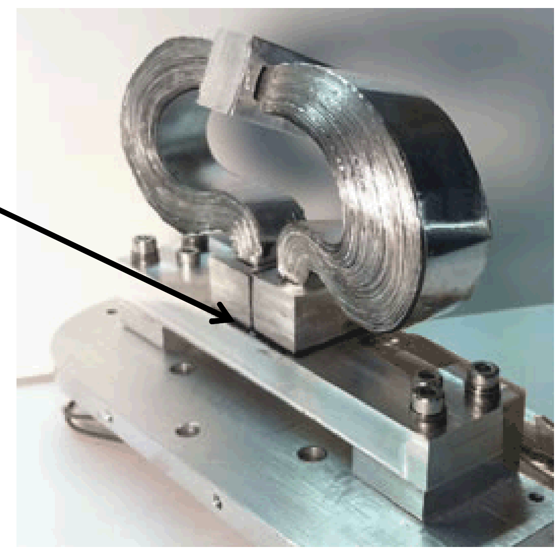


Elastomeric TIMs

Thermal straps



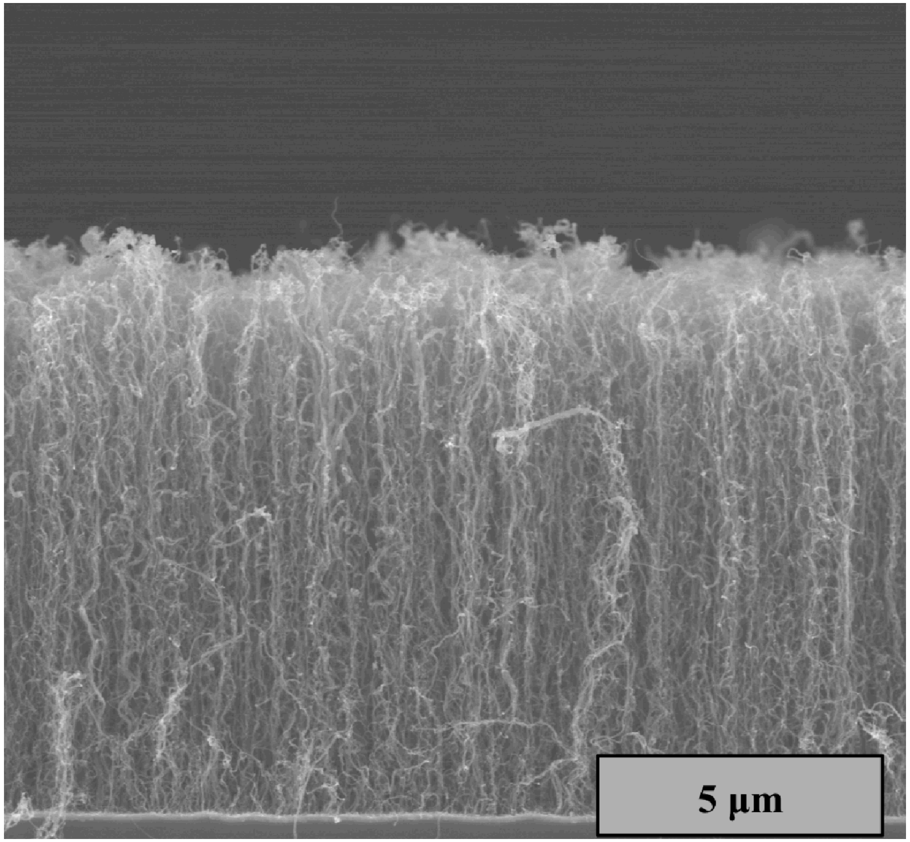
CNT TIMs
(or metal foil)



www.thermotive.com

CNT-TIM Fabrication

- CNTs were grown on a Si substrate with a tri-layer catalyst
  - 30 nm Ti
  - 10 nm Al
  - 5 nm Fe
- Microwave plasma chemical vapor deposition (MPCVD) was used to grow CNTs
  - N_2 anneal
  - 2.5 minute growth
    - 800^{o}C
    - 300 W
    - 10 Torr
    - 50 sccm H_2, 10 sccm CH_4



Radiation Dosing

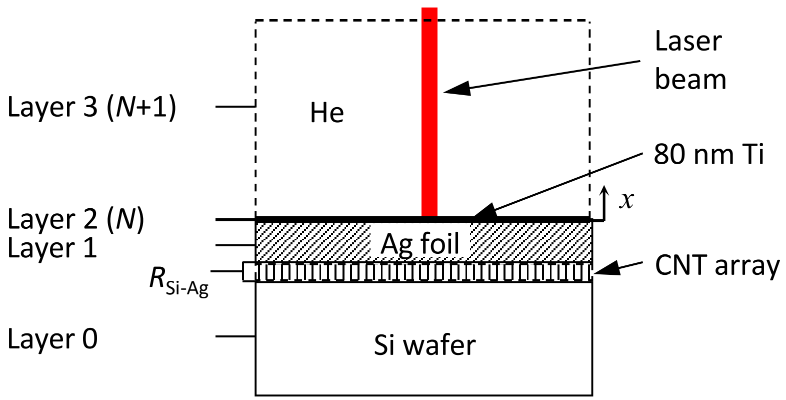
- Accelerated radiation aging was conducted in a ^{60}Co gamma cell
  - 250 rad/sec
  - Total doses of 50 and 100 Mrads
  - Dose chosen to be consistent with a previous study on elastomeric TIMs [3]

[3] R. Sayer et al., 2013, ASME Summer Heat Transfer Conference, HT2013-17408

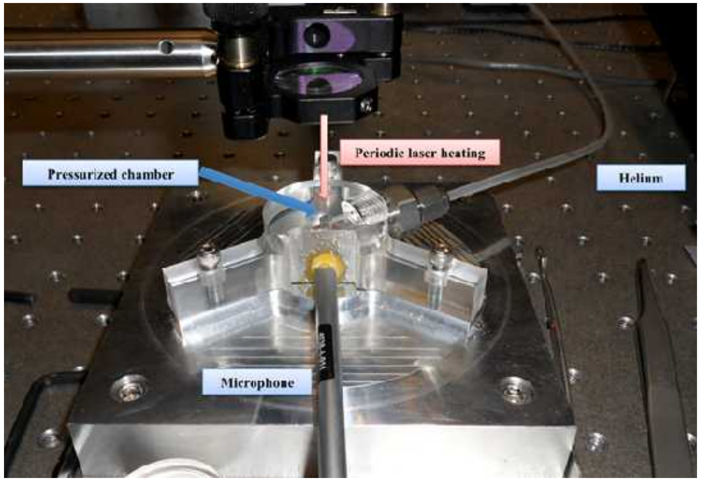
Raman Spectroscopy

- Technique used to observe low-frequency modes in a system
  - Provides a molecular fingerprint of materials
- Renishaw InVia Raman microscope
  - 488 nm Ar laser
  - 1 µm spot size
  - 110 s acquisition
  - 5 locations on each sample
  - 3 different CNT samples for each dose

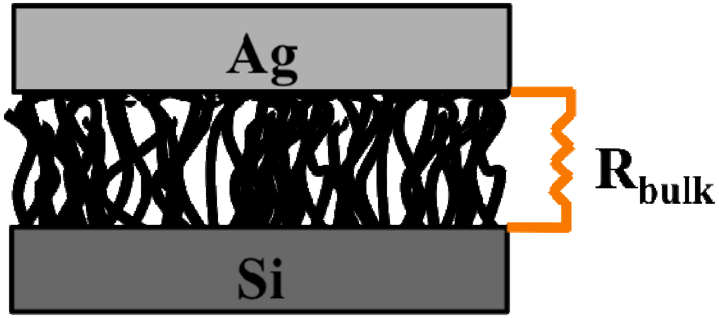
Photoacoustic (PA) Technique



H. Hu et. al, *J. Appl. Phys.* **86**, 7 (1999)
B.A. Cola et. al, *J. Appl. Phys.* **101**, 054313 (2007)

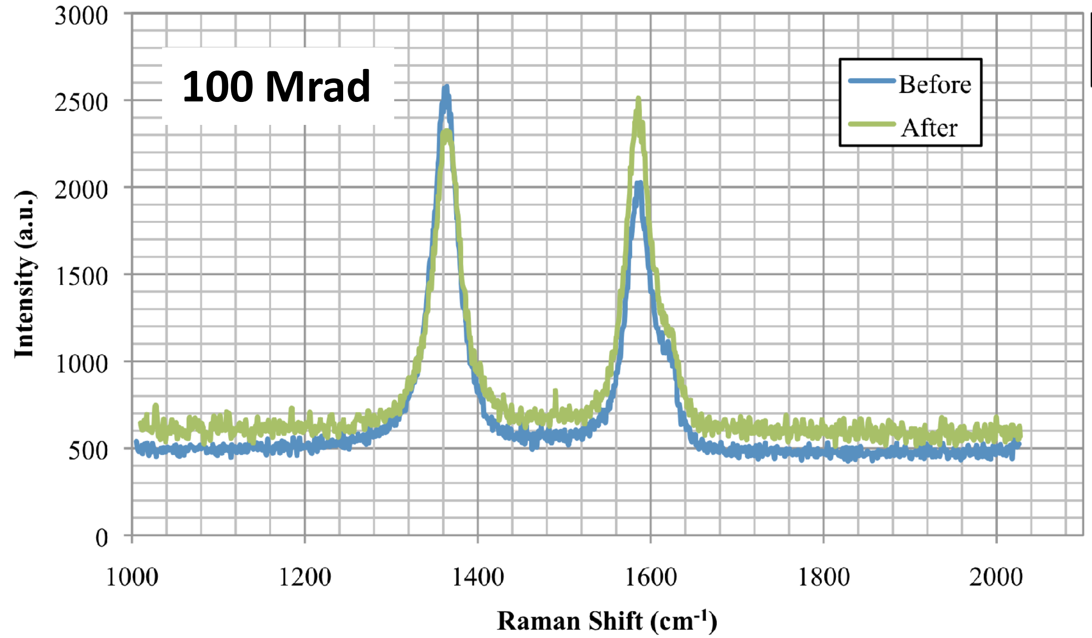


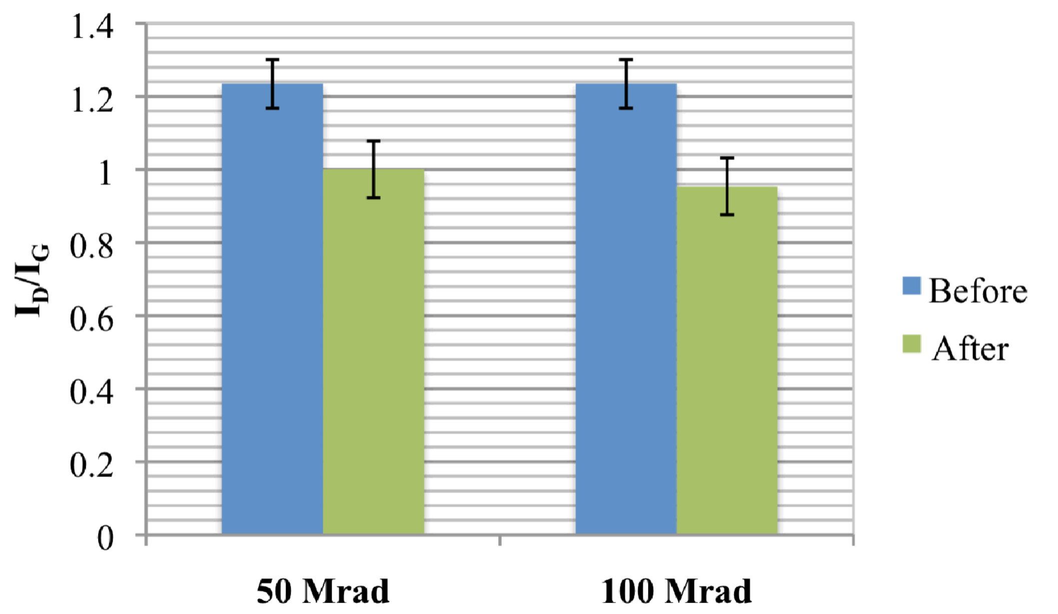
- Near IR laser irradiation
- Measurement of multilayered sample enabled by laser irradiation at modulated frequencies (300 – 1000 Hz)
- Sample heating causes 'thermal piston' effect in He gas layer which is monitored by a microphone



Results: Raman Spectroscopy

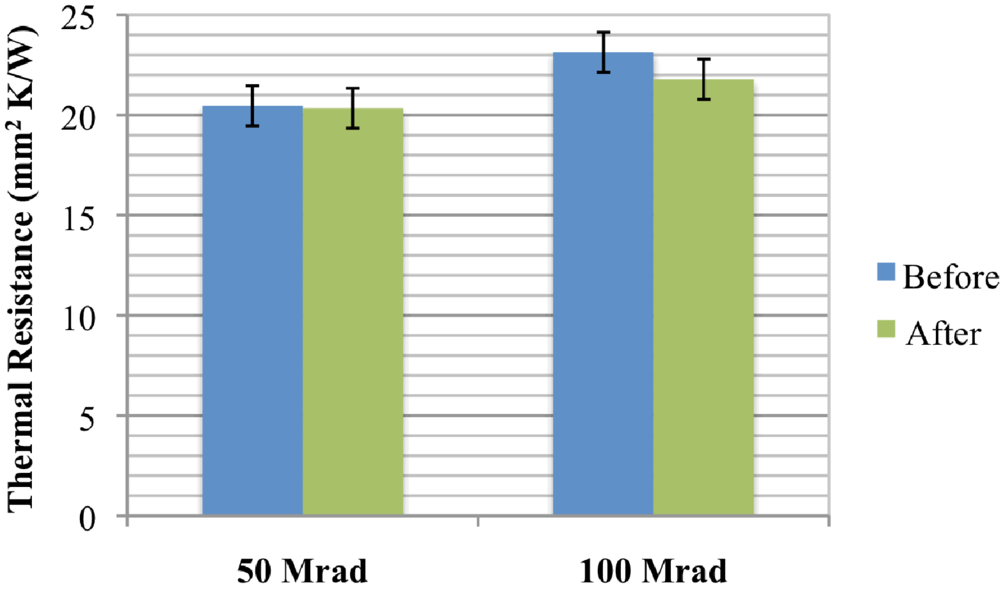
- D-peak (1360 cm^{-1}):
  - Related to vibrational modes associated with edges of graphene
  - Indicates disorder
- G-peak (1585 cm^{-1}):
  - Associated with E_{2g} optical phonons in graphene
- D'-peak (1620 cm^{-1})
  - Related to finite size effects in the CNTs
- I_D/I_G ratio used to qualitatively determine the relative amount of defects present
  - Ratio decreases with gamma radiation dose
  - Improved graphitic order in tube walls





Results: Thermal Contact Resistance

- Each triplicate of CNT-TIMs were measured before and after irradiation
- Contact pressure: 134 kPa
- Slight decrease in TCR after gamma irradiation
  - Within experimental error of the PA technique.
- <u>Thermal performance does not degrade under gamma-ray irradiation</u>
  - CNTs are naturally ‘rad hard’



Conclusion

- CNT-TIMs were subject to 50 and 100 Mrad of gamma radiation to represent 5 and 10 year missions, respectively
- The I_D/I_G ratio decreased from 1.3 to 1.0 for the 50 Mrad samples and from 1.3 to 0.95 for the 100 Mrad samples
  - Improved graphitic order
  - Radiation annealing
- TCR was not affected by gamma radiation
  - Thermal performance of the CNT-TIMs does not degrade over time
  - This ‘rad hard’ quality is desirable in space systems

Acknowledgments

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