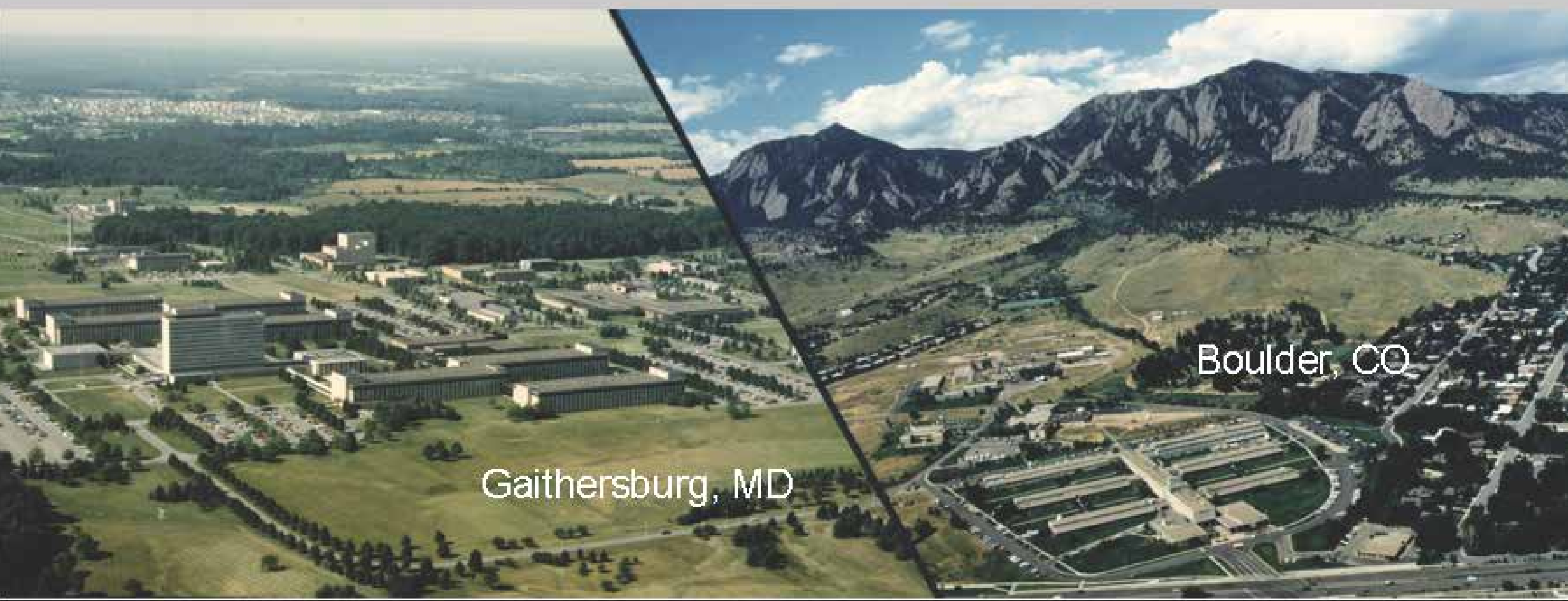
April 2014

Carbon Nanotube Absolute Radiometer

J.H. Lehman
National Institute of Standards and Technology
325 Broadway, Boulder, Colorado 80305-3228
lehman@boulder.nist.gov

(portions of this work are presented elsewhere)

Where



Physical Measurement Laboratory
Quantum Electronics and Photonics Division
National Institute of Standards and Technology

Thanks

Nathan Tomlin, Malcolm White & Solomon Woods
National Institute of Standards and Technology

Theo Theocharous & Chris Chunnilall
National Physical Laboratory, Teddington - UK

Andreas Steiger, Christian Monte, Ralf Mueller & Mathias Kehrt
Physikalisch-Technische Bundesanstalt, Berlin Germany

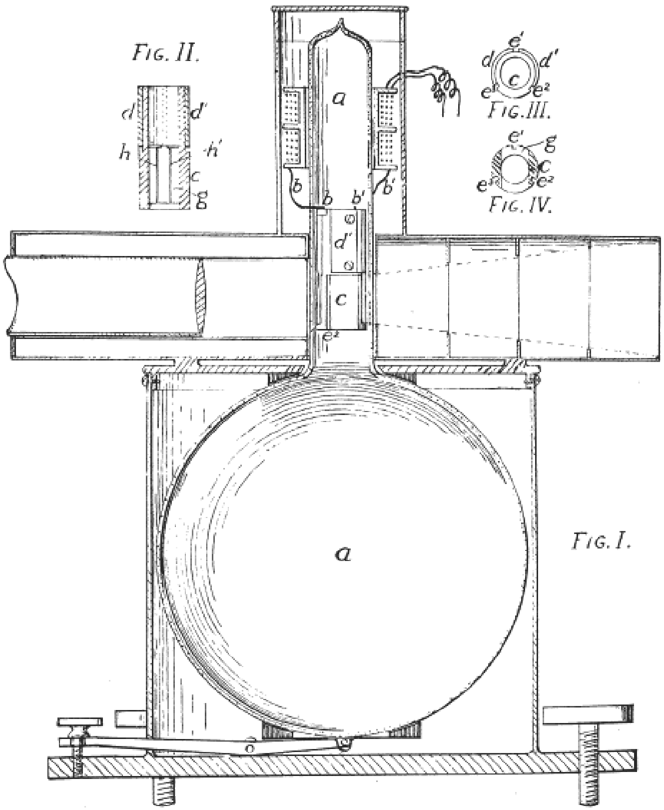
Erik Richard, Dave Harber, Greg Kopp, Karl Heuerman & Ginger Drake
Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder

Unterstützt von / Supported by
Alexander von Humboldt
Stiftung / Foundation

History

Samuel Langley's bolometer, 1887

ANNALS OF THE ASTROPHYSICAL OBSERVATORY Vol. 6 1881



1. The Make-up of the Bolometer

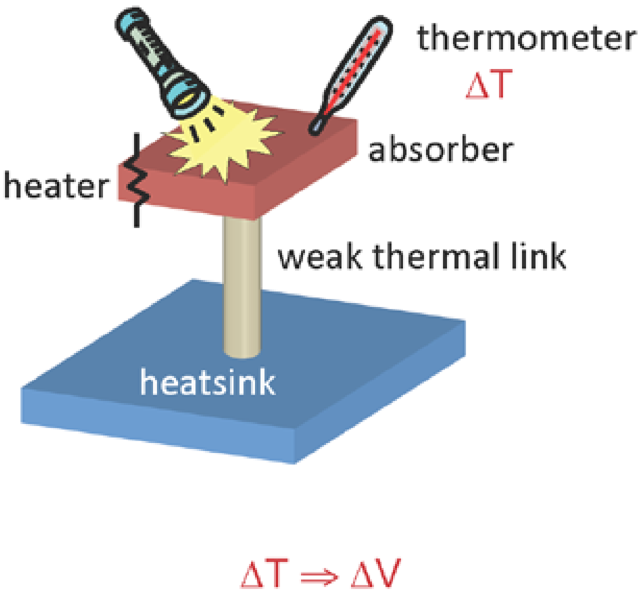
Sensitive strips *h*, *h'* mounted on the copper blocks *c*, *d'* form two arms of a Wheatstone's bridge, completed by the two coils *b*, *b'*. Solar spectral rays are admitted by a vestibule with diaphragms, and may be adjusted by the eyepiece. The vessel, *a*, is highly evacuated.

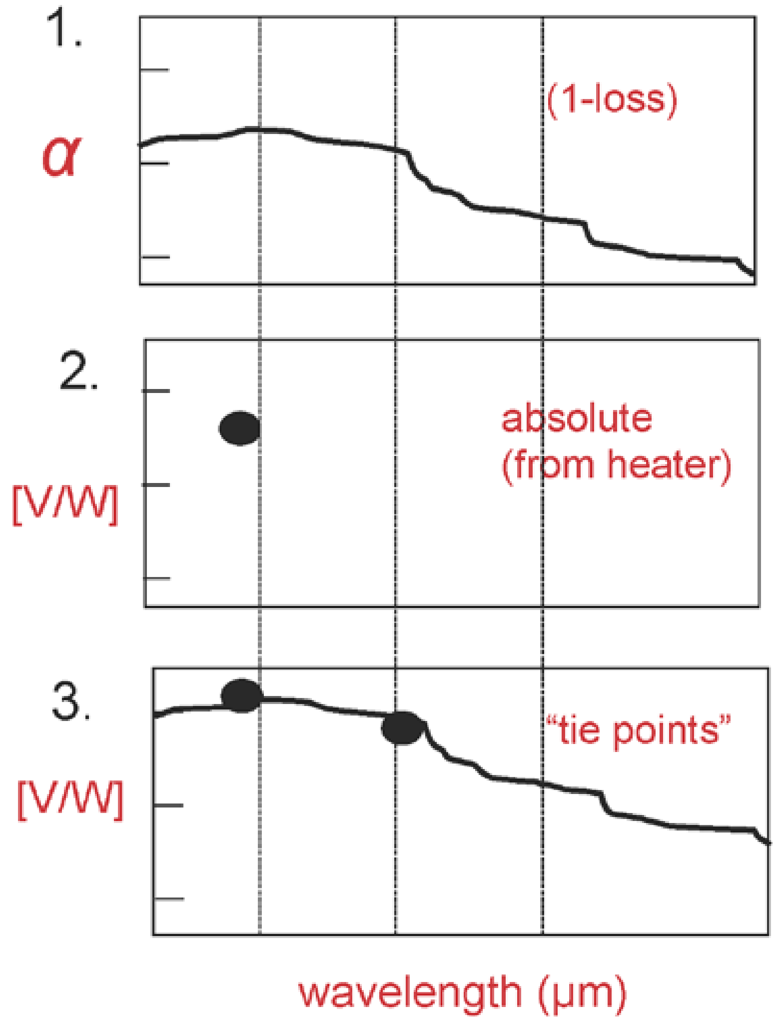
http://www.hao.ucar.edu/public/education/sp/images/langley.html

"Langley's chief scientific interest was the sun and its effect on the weather, and believed that all life and activity on the Earth were made possible by the sun's radiation."

"Langley's bolometer was so sensitive that it could detect thermal radiation from a cow a quarter of a mile away."

Laser Radiometer Design





Cryogenic Radiometer Design

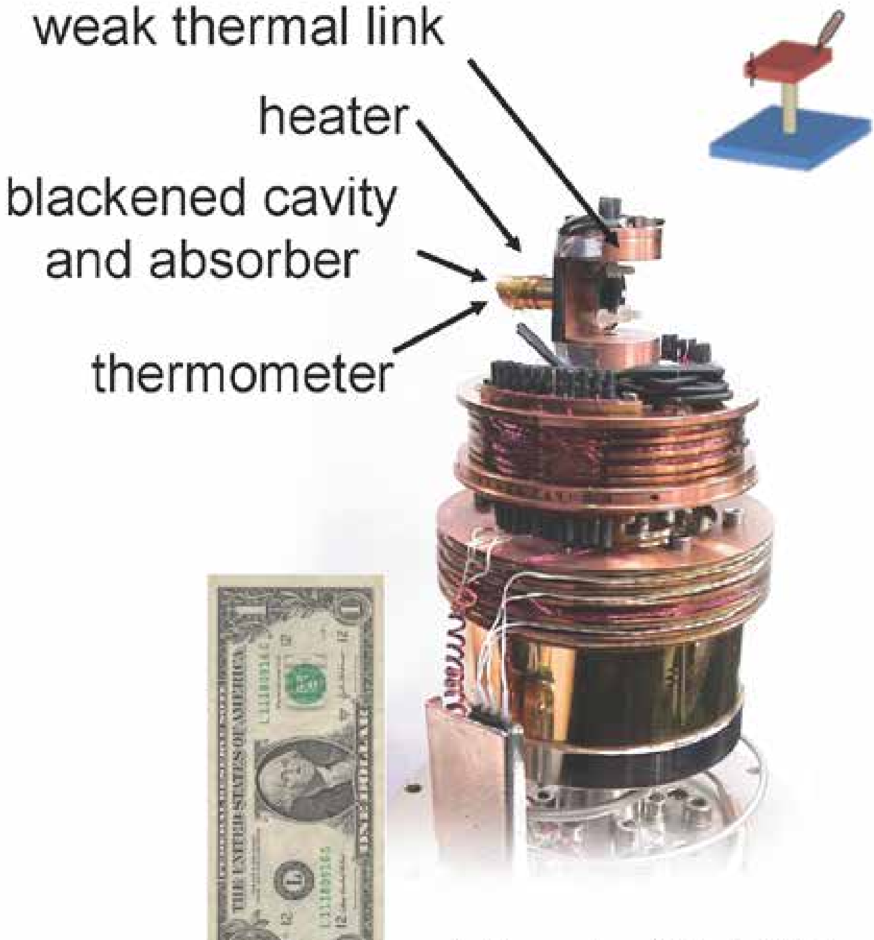


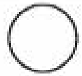
photo: courtesy Malcolm White

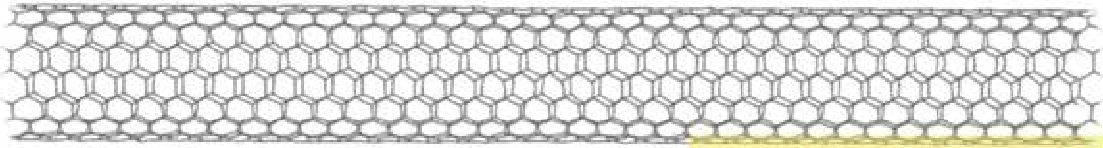
Martin, et al., , Metrologia, 21, 1985

Carbon nanotubes (are black)

Carbon Nanotubes

Single-wall Carbon Nanotubes

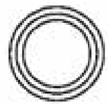


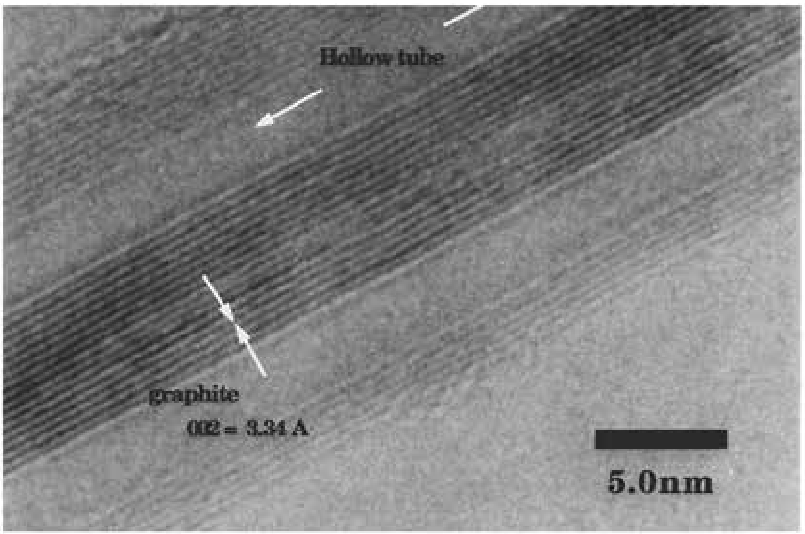


Not spectrally uniform

Single sheet of graphene wrapped into a tube: microns in length, ~1-2 nm diameter, capped (Iijima, 1993).

Multi-wall Carbon Nanotubes



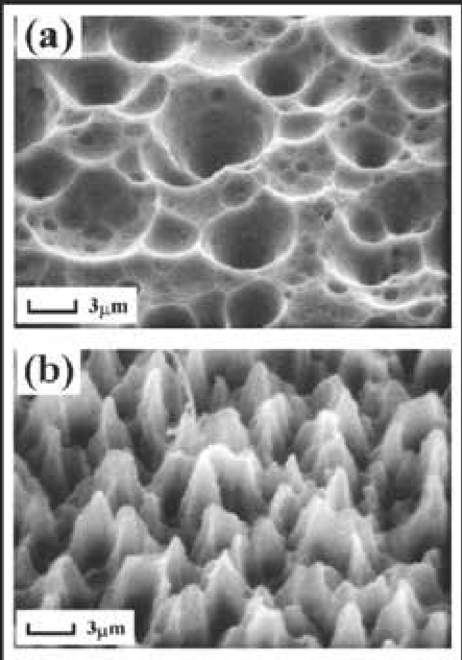


Concentric cylinders of graphite with a hollow center, capped (Iijima, 1991)

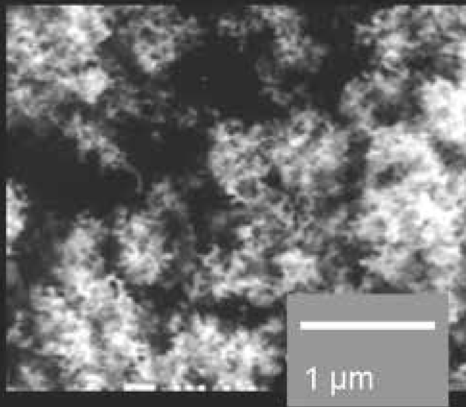
Very spectrally uniform

Absorber Morphology, Black Coatings

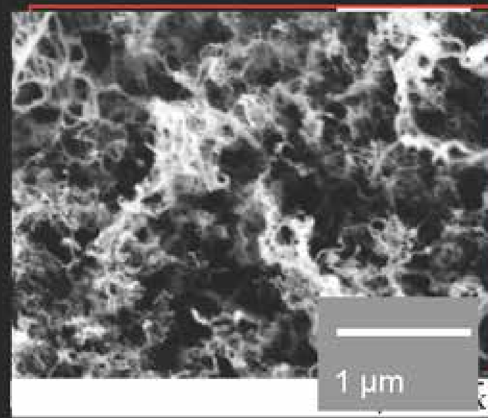
Nickel phosphorous



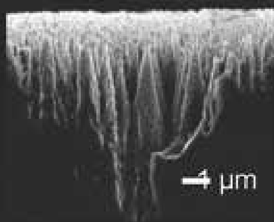
Gold black
"nano fractal gold"



Bulk
carbon nanotubes



Silicon



Black silicon

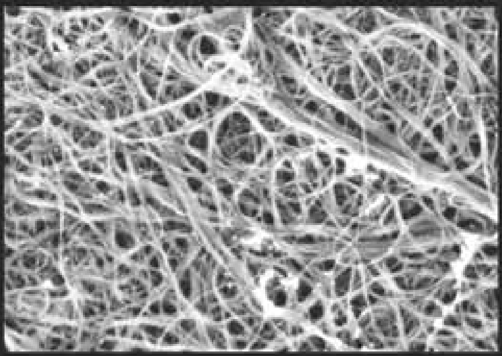
A. Brenner and G. E. Riddell, J. Res. Natl. Bur. Stand. (U. S.), 1946, 37, 1991.

R.J.C. Brown, P.J. Brewer and M.J.T. Milton, J. Mater. Chem., 2002, 12, 2749–2754

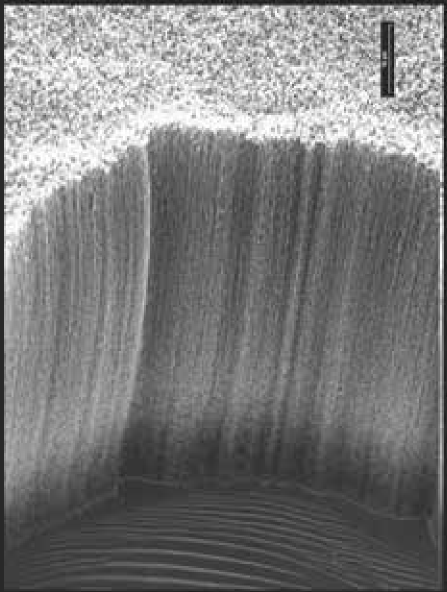
Lehman, J.H., Theocharous, E., Eppeldauer, G., Pannell, C., Meas. Sci. Technol. **14**, 916-922, (2003).

J. E. Carey, C. H. Crouch, E. Mazur, Opt. & Phot. News, Feb (2003)

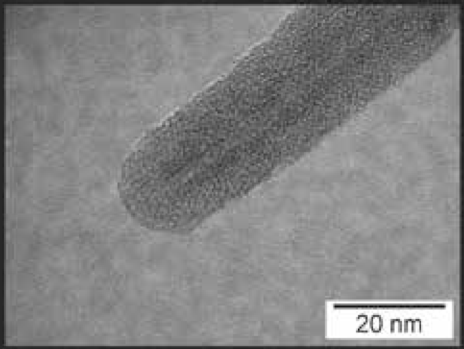
Materials



mats

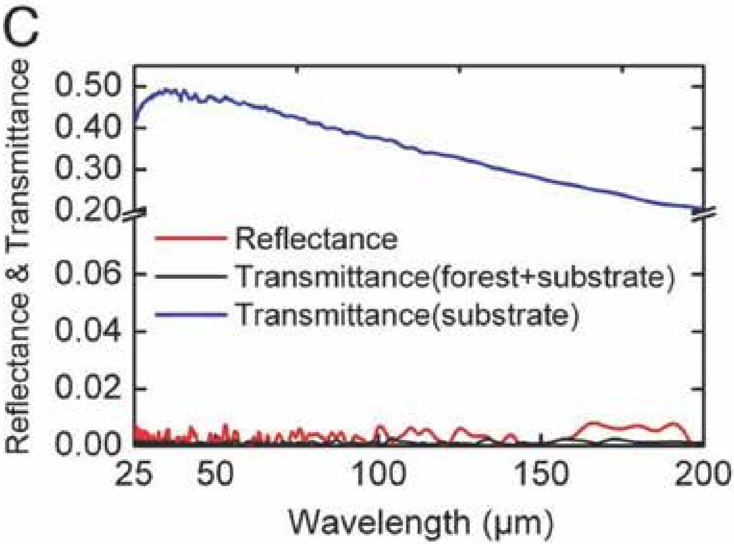


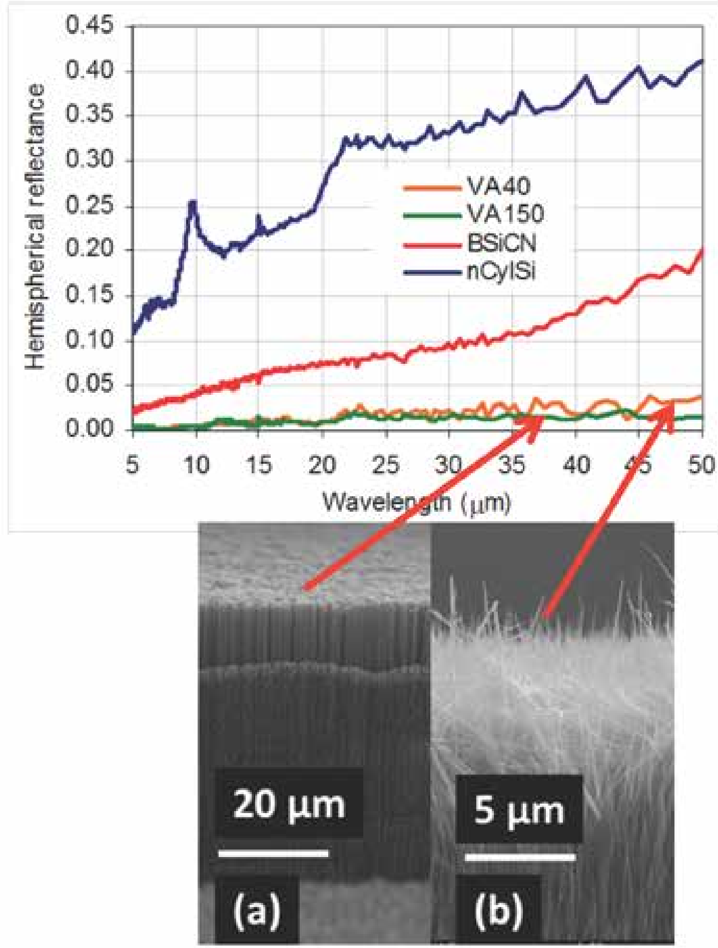
arrays



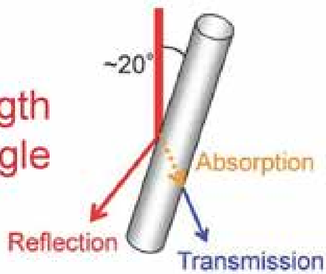
composite

Low density, 'rough' and low non-nt content



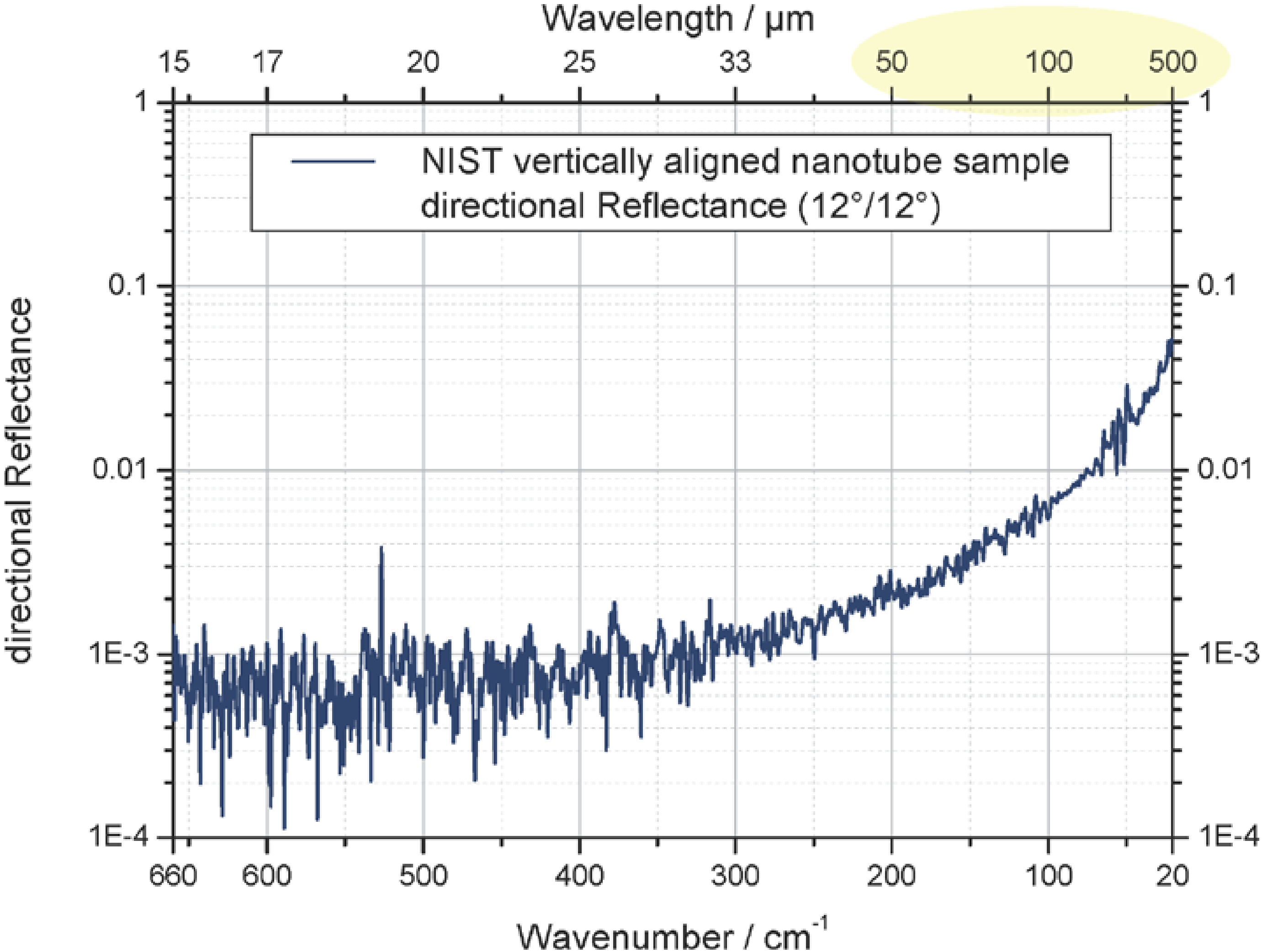


rough
⇒ varying length
⇒ varying angle



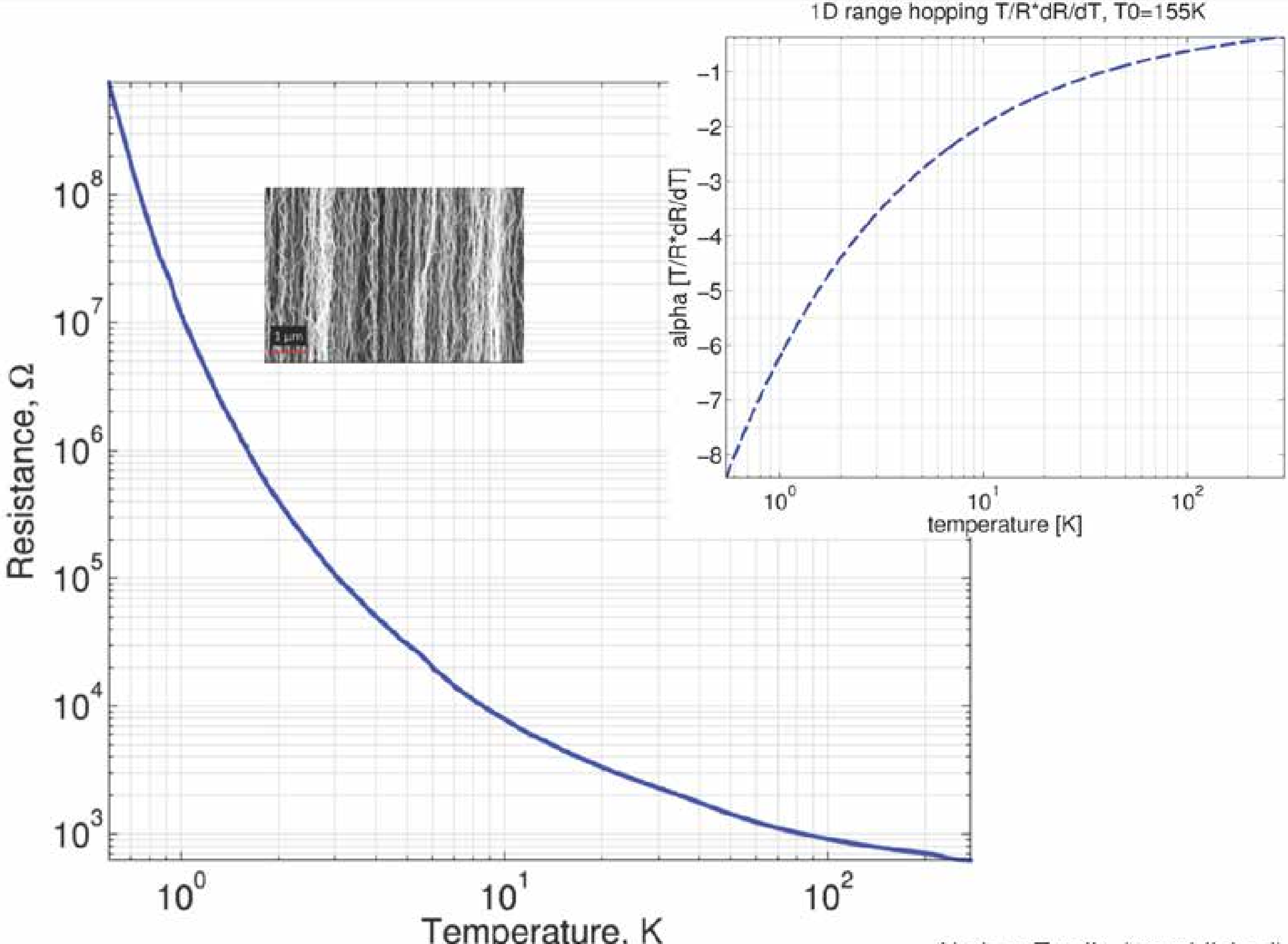
Mizuno et al., PNAS, 106 6044–6047 2009.
Chunnilall et al., Carbon, 50, 5340-5350, 2012.

FIR reflectance

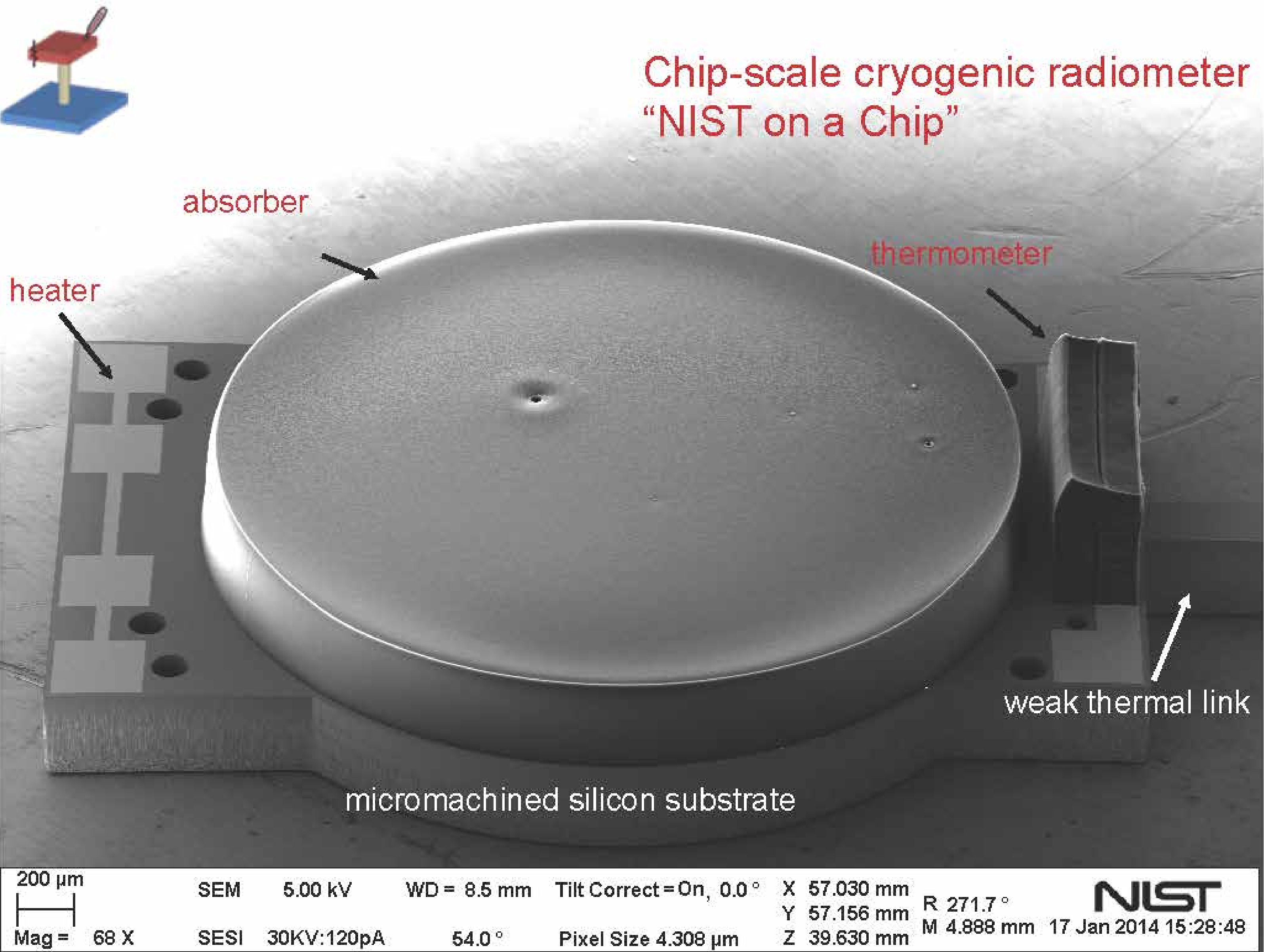


PTB, Department 7.3, M. Kehrt, C. Monte

Temperature coefficient

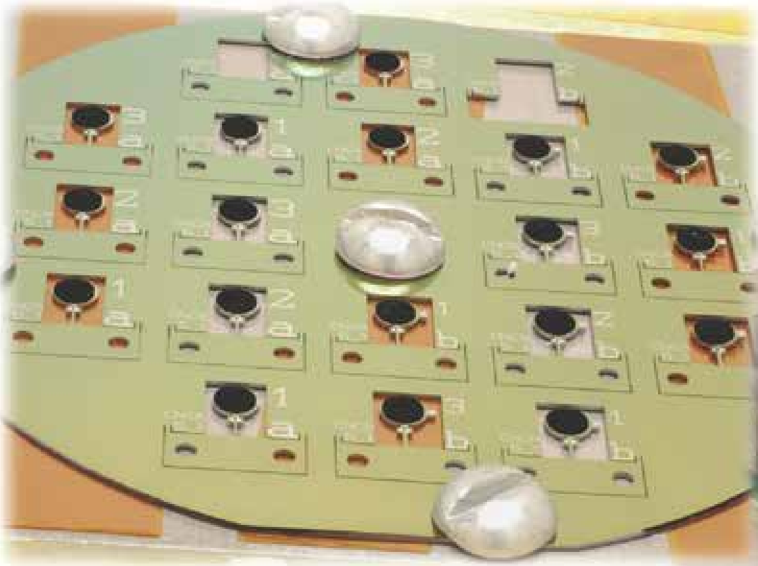


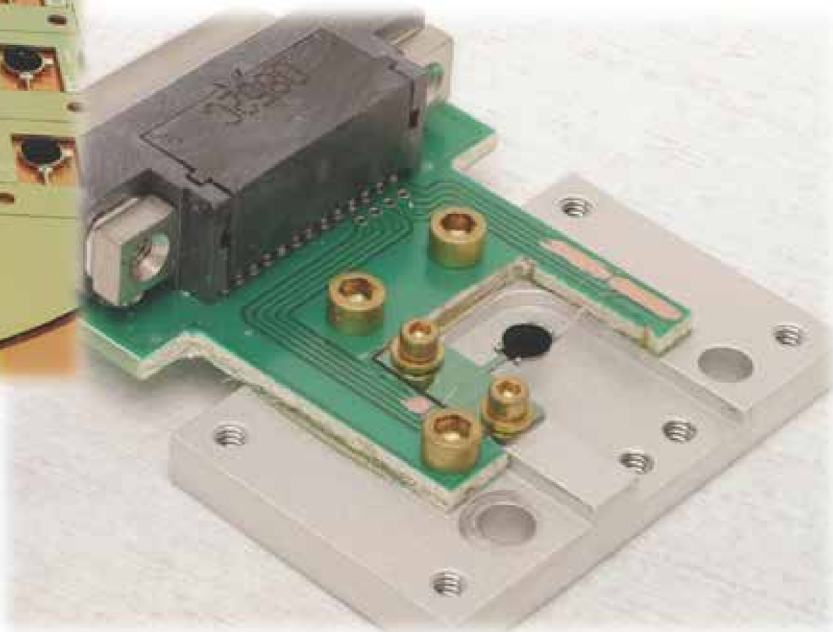
Nathan Tomlin (unpublished)


Chip-scale cryogenic radiometer
"NIST on a Chip"
absorber
thermometer
heater
weak thermal link
micromachined silicon substrate
200 µm
Mag = 68 X
SEM 5.00 kV
SESI 30KV:120pA
WD = 8.5 mm
54.0 °
Tilt Correct = On, 0.0 °
Pixel Size 4.308 µm
X 57.030 mm
Y 57.156 mm
Z 39.630 mm
R 271.7 °
M 4.888 mm
17 Jan 2014 15:28:48

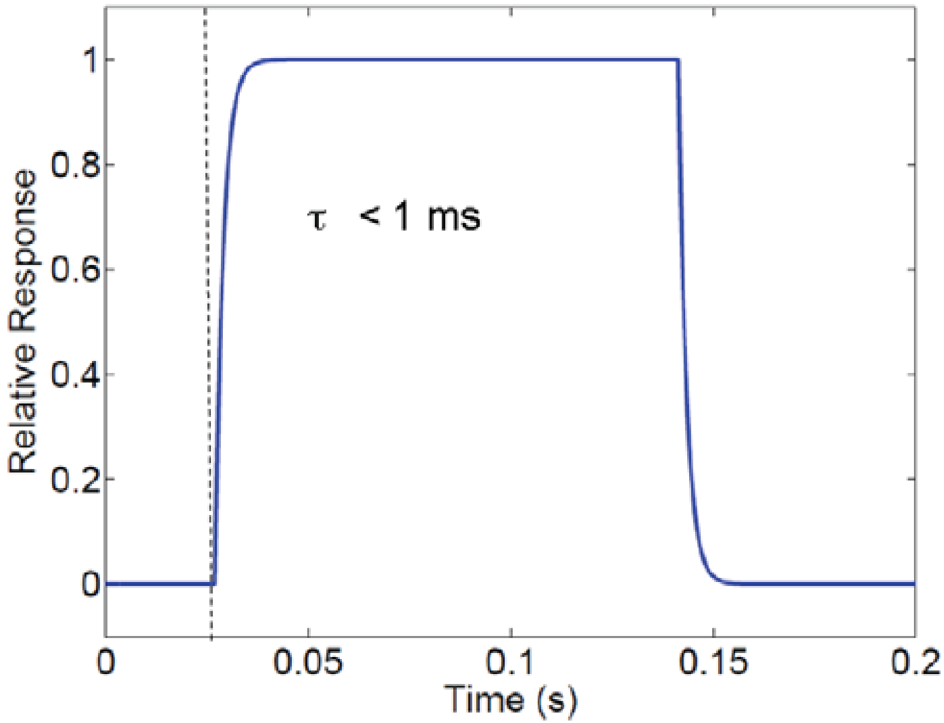
Laser Radiometry

Carbon nanotube electrical substitution bolometers





Temporal Response



New opportunities for a broadband radiometer e.g., FTIR

Cryogenic Radiometer Design

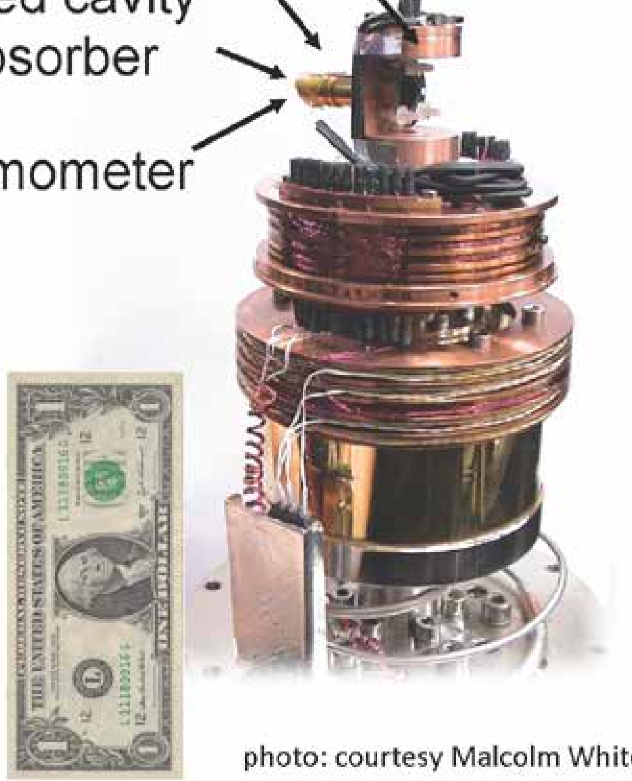
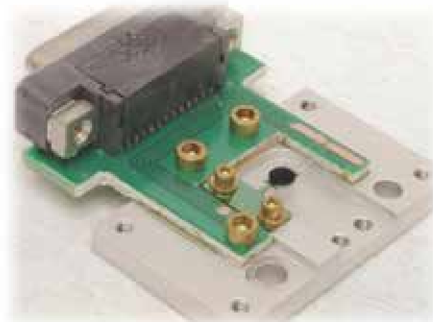
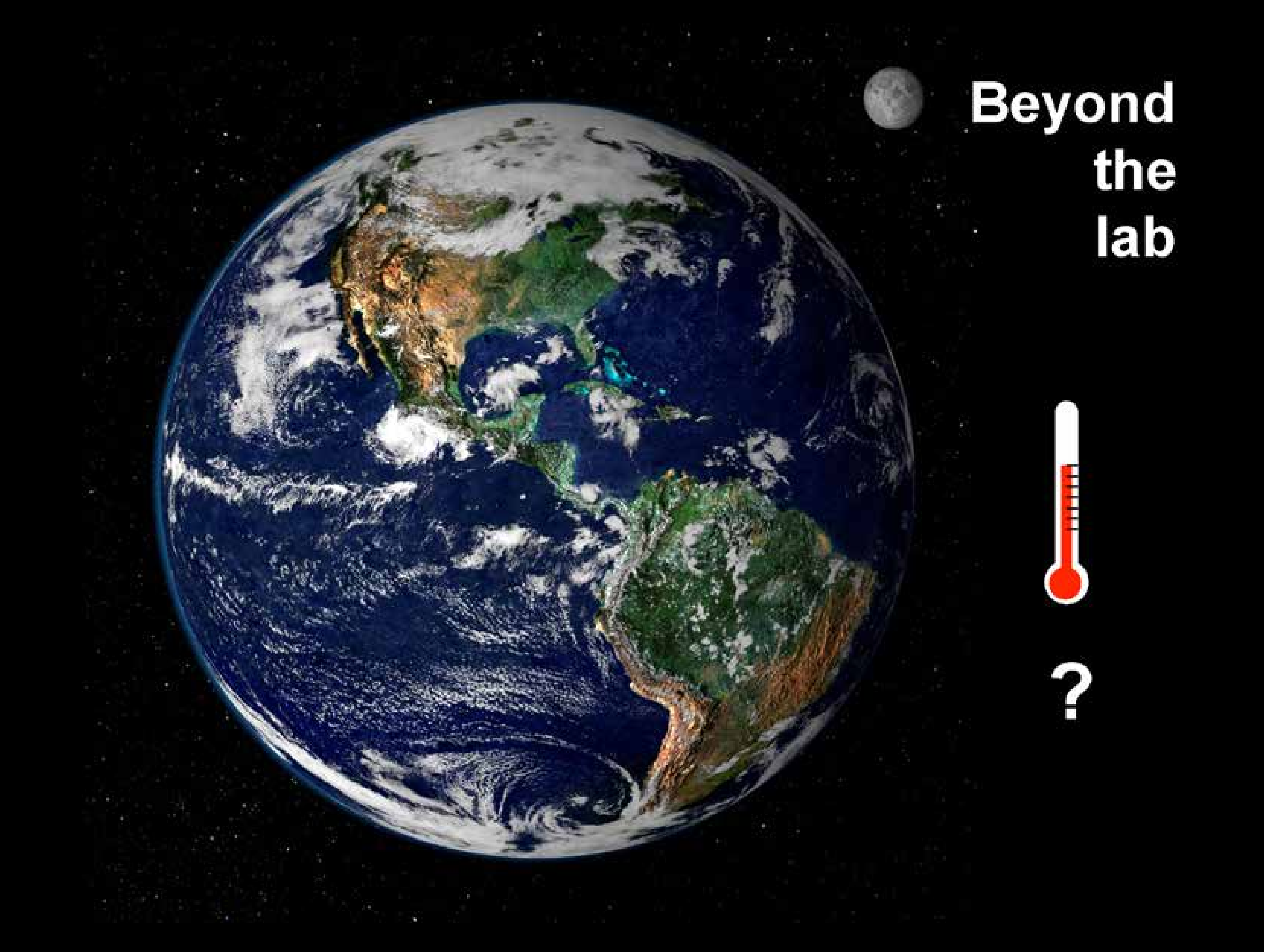


photo: courtesy Malcolm White

Black
Broad Wavelength
Fast
Sensitive
(cheap?)

=




Beyond
the
lab
?

The Vision

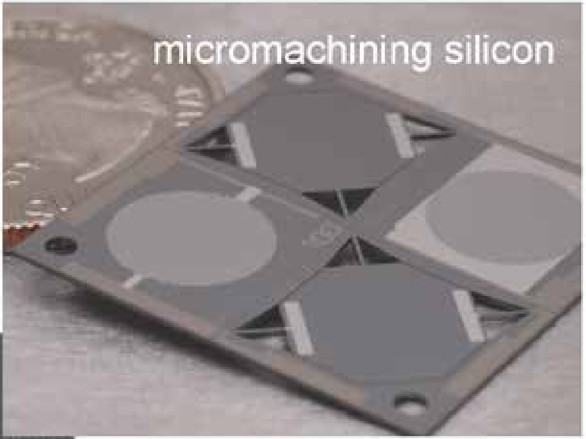
Not all of problems are strictly technical
(some are logistical or administrative)

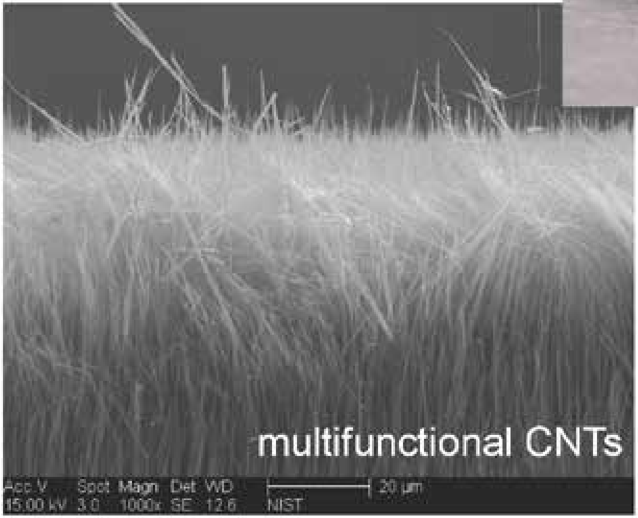
"NIST-on-a-Chip"

Field Deployment (reduced downtime)

NIST traceability, ease of use, robust

Adapt the technology to other missions
(e.g.,, space)

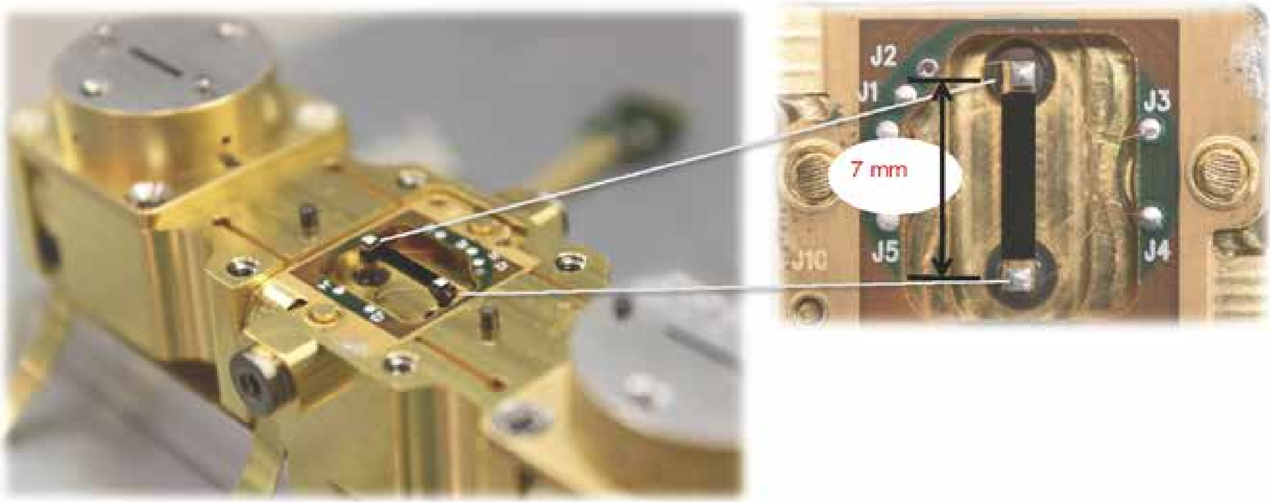


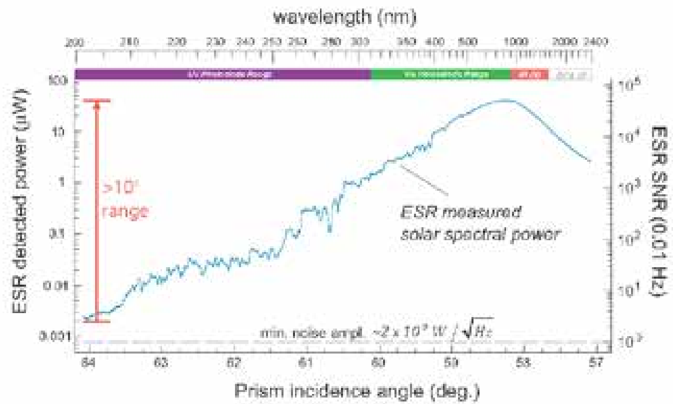


small refrigeration for small things

SIM Electrical Substitution Radiometer (ESR) - Overview

TSIS ESR Bolometer Detail





Present technology (SORCE & TSIS)

NiP Black on CVD diamond substrate

- *low yield process (hit-or-miss*
- *non-uniform absorptance*
- *difficult & expensive fabrication*

Proposed advancement (CSIM)

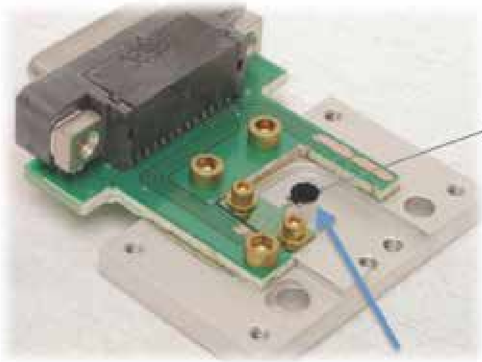
Carbon nanotube (CNT) Black on Si substrate

- *high yield process (precise control)*
- *very uniform absorptance*
- *rapid micromachining fabrication*

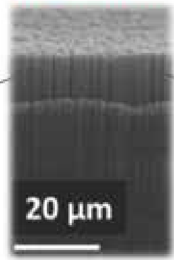
Carbon nanotube (CnT) bolometers ideally suited for CSIM ESR

NIST Nanotube Radiometer (Gen II)

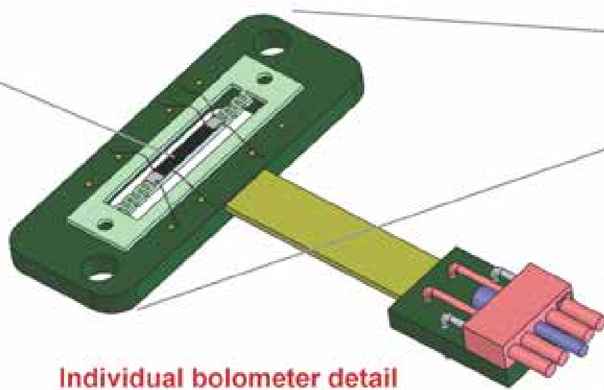
Proven technology



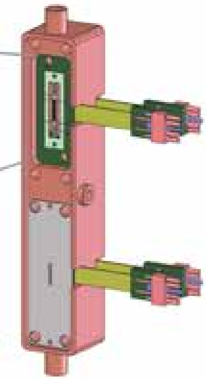
CNTs on Si substrate

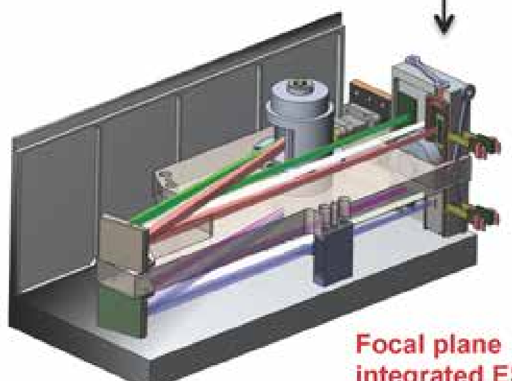


Compact SIM ESR Concept



Individual bolometer detail





Focal plane integrated ESR

Advantages

- ***Broad and uniform responsivity 10^2 nm to 10^5 nm***
- ***Mastery of thermal conductance "G"*** *– radiometer can be optimized for a given power range via heat link design*
- ***Large area, fast*** *–milliseconds rather than minutes*
- ***Low risk, very repeatable process control*** *(micro-machined wafers)*

(One more thing related to nanotubes and micromachining silicon)

HyperSpectral Imager for Climate Science (Kopp)

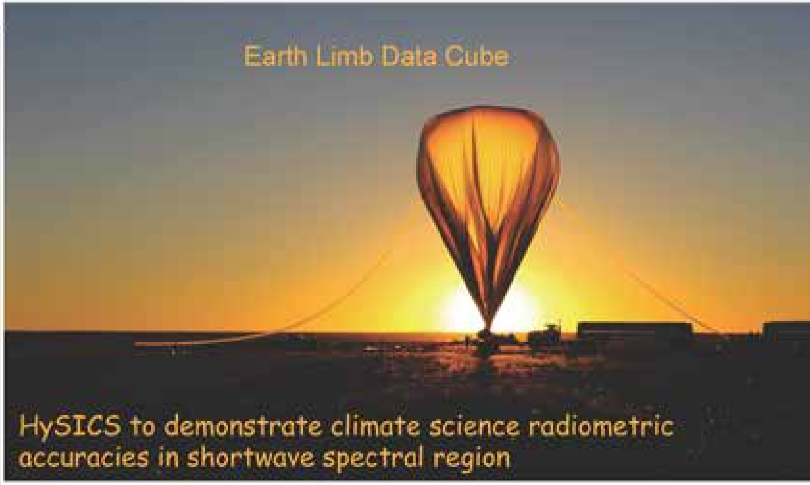
Objective

Build and flight test (2x) a hyperspectral imager

350-2300 nm with single FPA to reduce cost & mass

- <0.2% (k=1) radiometric accuracy
- <8 nm spectral resolution
- 0.5 km (from LEO) IFOV and >100 km FOV
- <0.13% (k=1) instrumental polarization sensitivity

to acquire sample Earth and lunar radiances



Approach

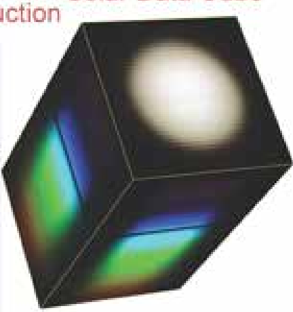
Single HgCdTe FPA covers full shortwave spectral range with reduced mass, cost, volume, and complexity

Incorporate solar cross-calibration approaches demonstrated on prior mission

Orthogonal configuration reduces polarization sensitivity.

Ground Reconstruction

Lunar Reconstruction

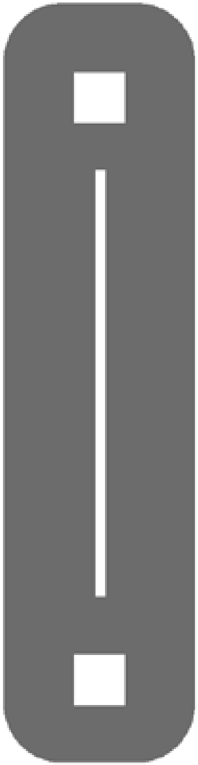


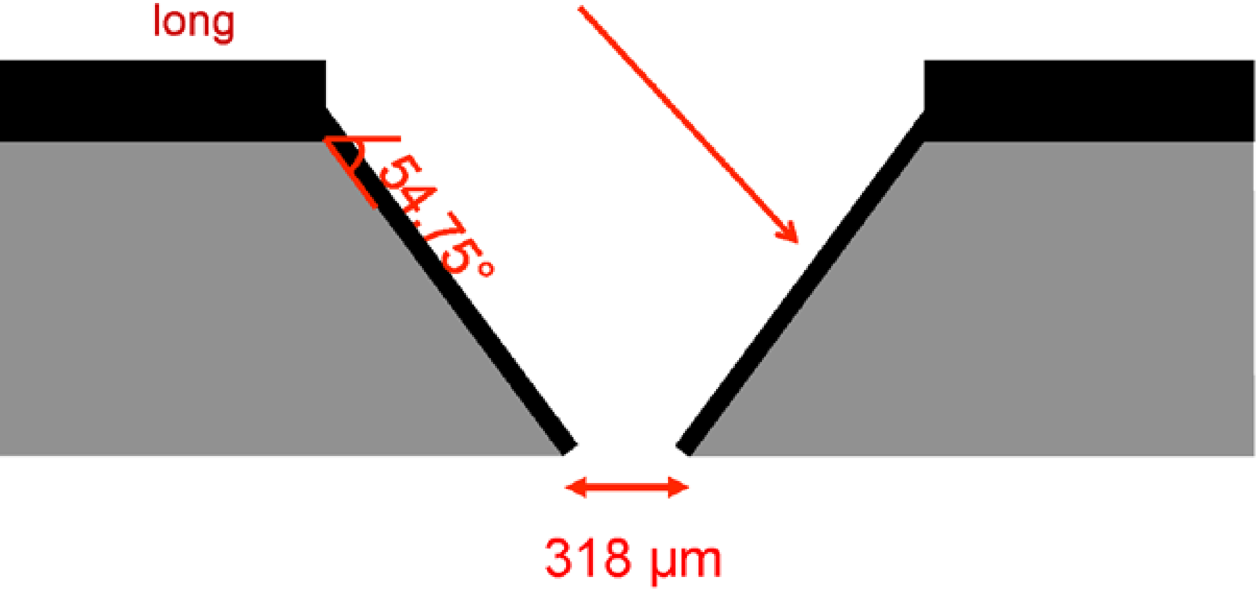
Solar Data Cube

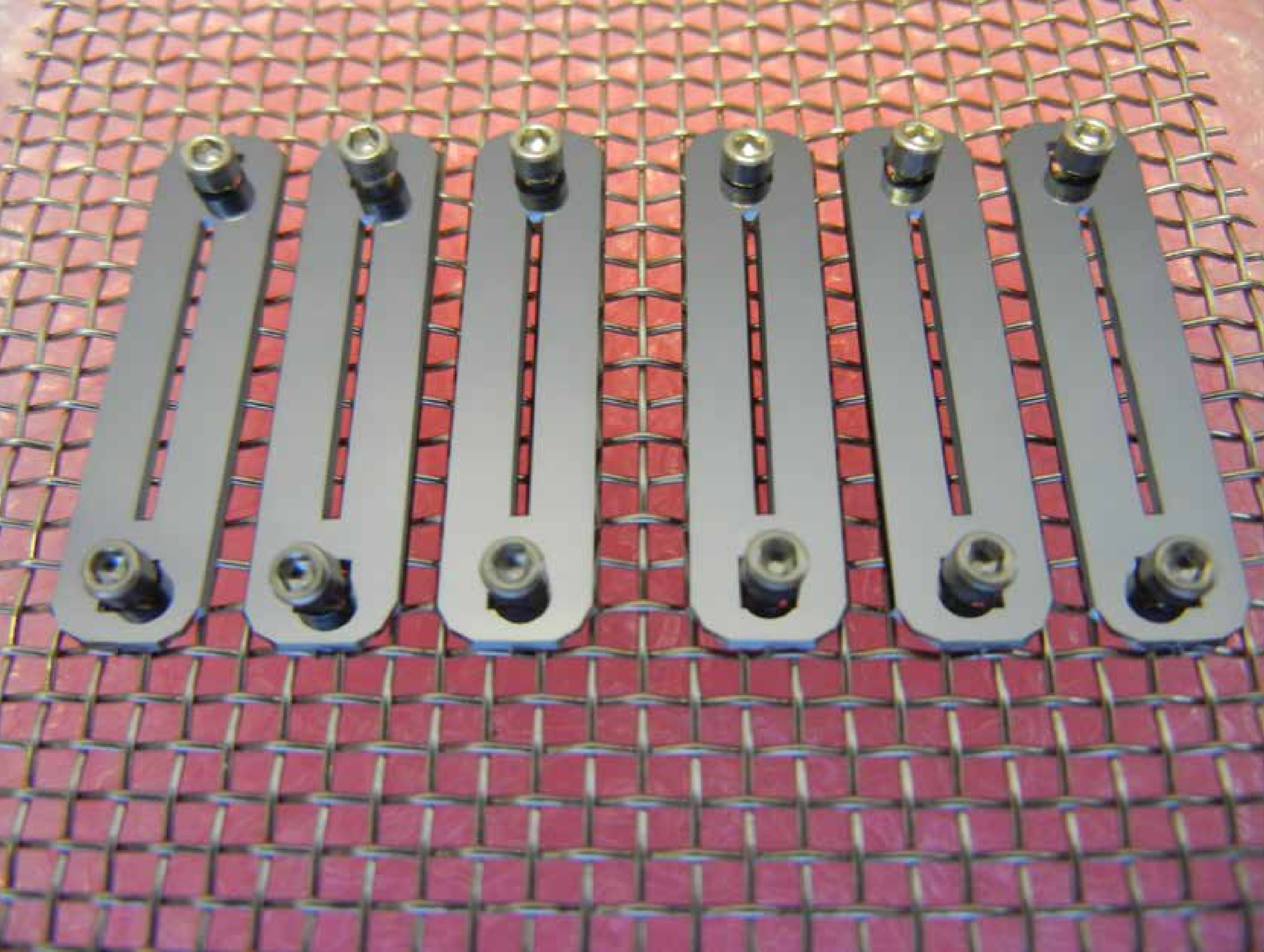
Co-Is: Peter Pilewskie / LASP Balloon Flight Manager – David Stuchlik / WFF

Nanotube masking chips:

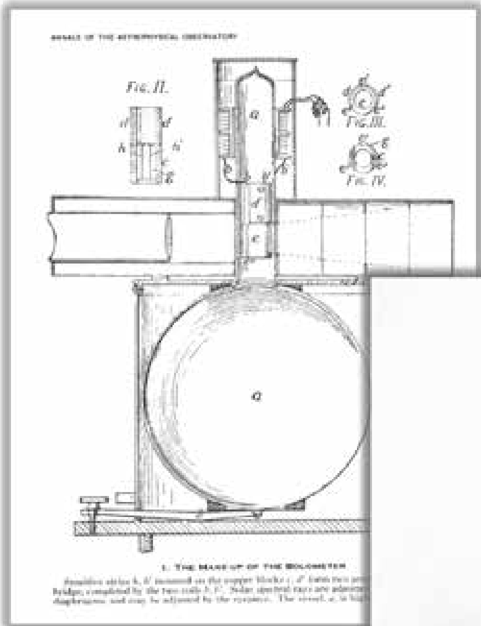
- Slit is KOH etched at 54.75 degrees
    - At small side: 318 um wide by ~13.9 mm long
    - At large side: ~770 um wide by ~14.4 mm long
- Square holes
    - 1.65 mm on a side
- Si chip thickness 325+-25 um
- 6 chips
- ***all above dimensions are just Si, not nanotubes****
- Vertically aligned carbon nanotubes, nominally 100 um long
    - We suspect nanotubes on angled surface are not very long



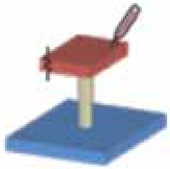




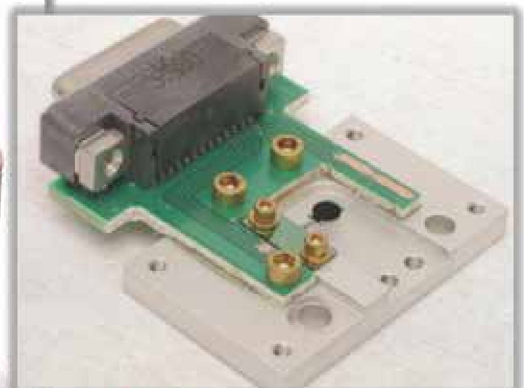
Cryogenic Radiometer Design



ca. 1885



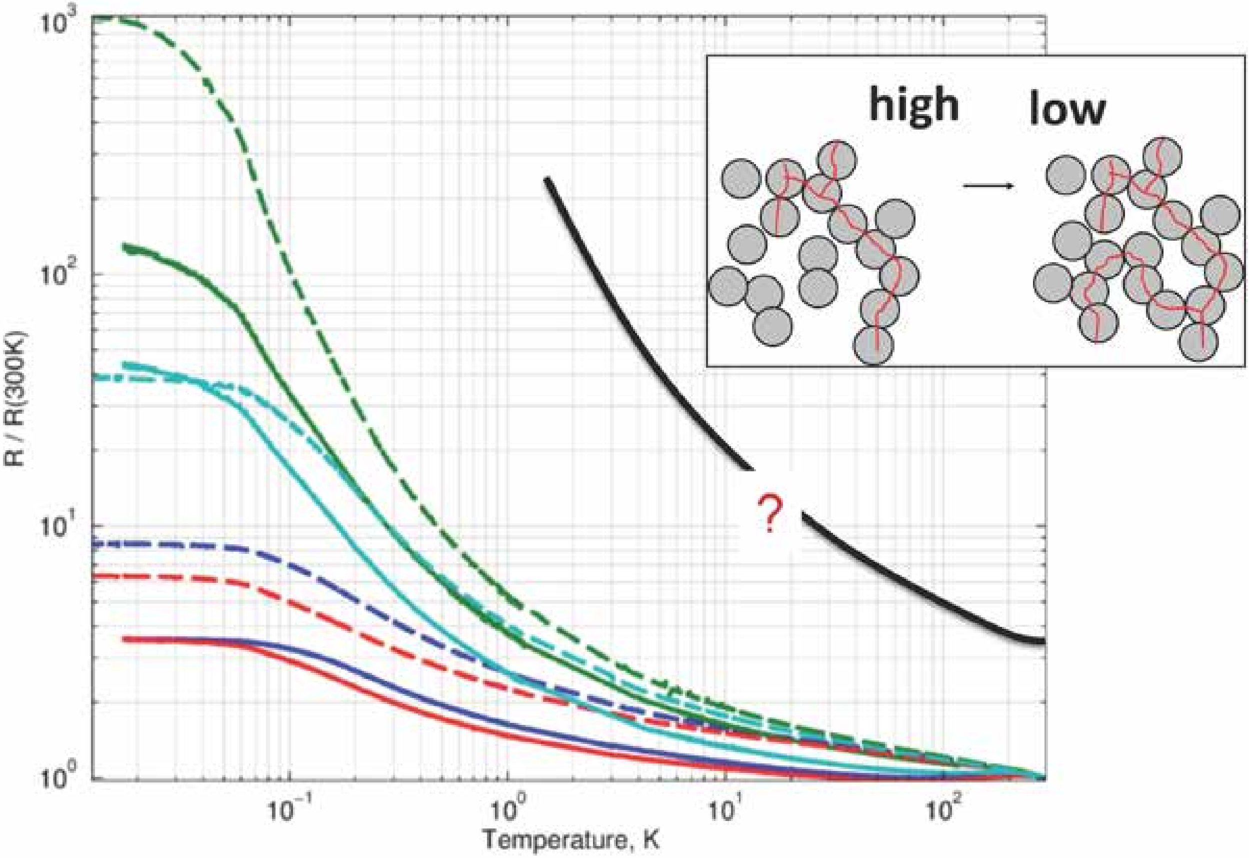
ca. 1985



2014

Black
Broad Wavelength
Fast
Sensitive

Temperature coefficient



Nathan Tomlin (unpublished)