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Progress in Carbon Nanotube Terahertz Photodetectors

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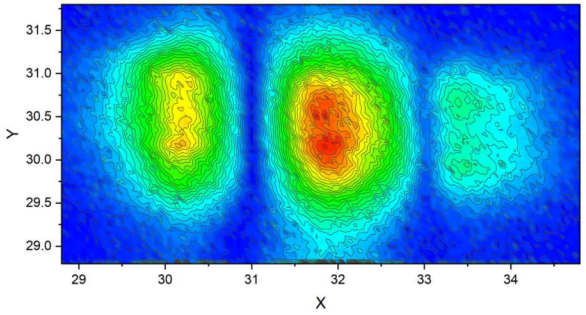
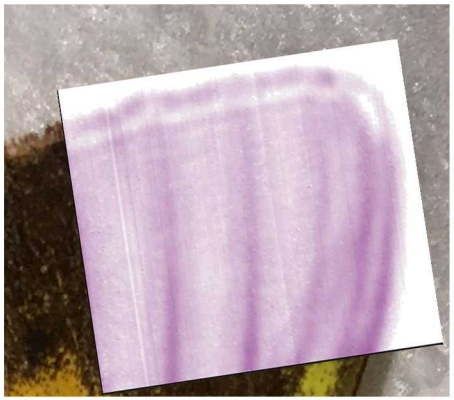
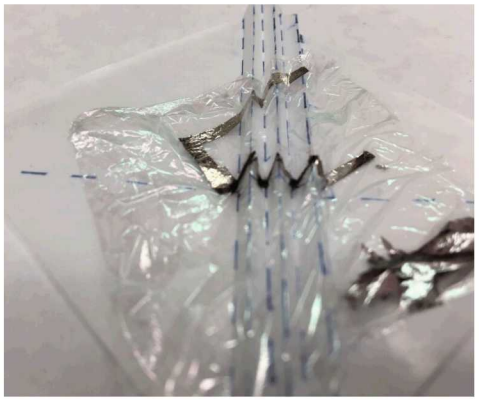
Livermore, CA







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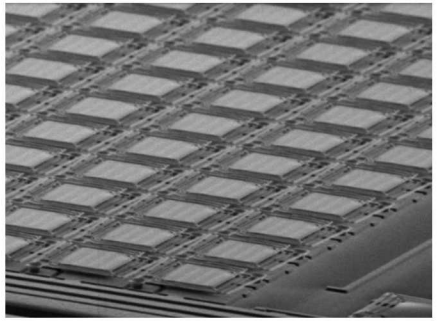
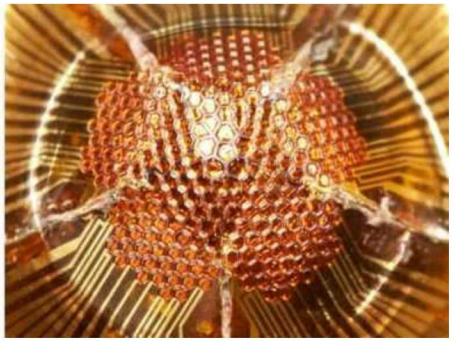
Photodetectors have traditionally been planar:



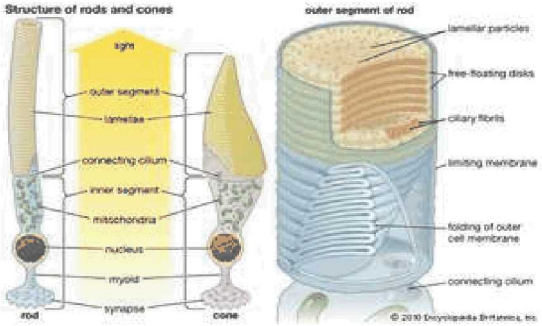
Next step is to consider curved detectors:



Zhang et al, Nat. Comm. (2017)

Nature is already a step ahead: 3D detectors

Human eye

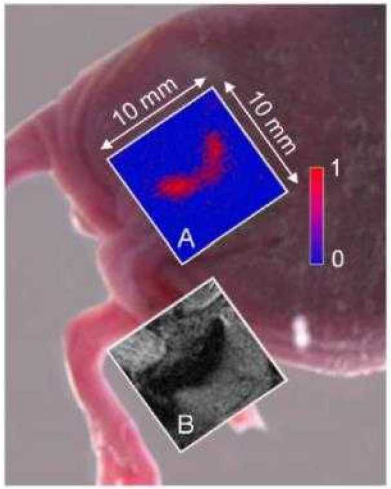


www.britannica.com

- **The future: complex 3D shapes that are dynamically reconfigurable**

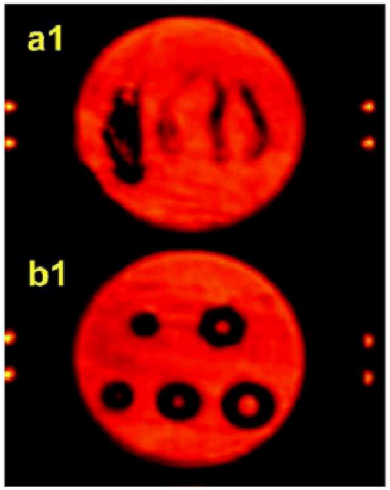
Terahertz is promising for a number of applications:

Medicine



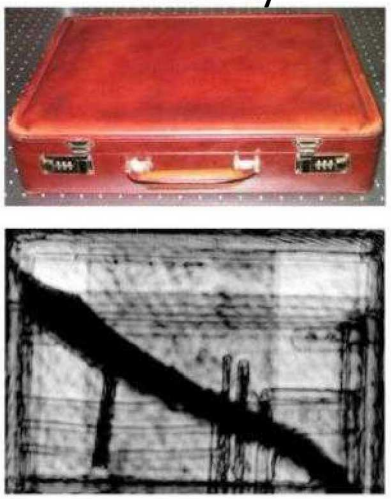
Park et al
IEEE Trans. THz S&T (2012)

Food inspection



Ok et al
Food Control (2014)

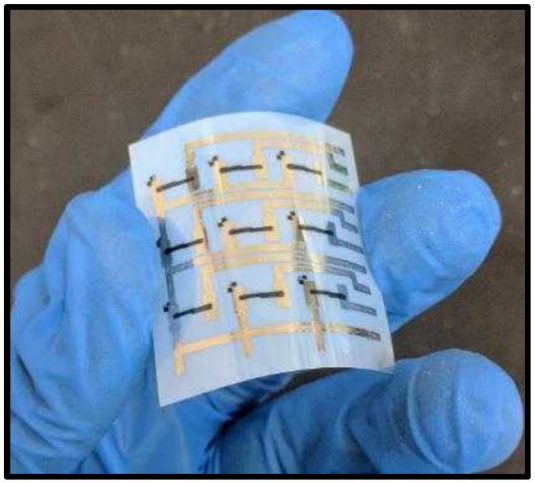
Security



Liu et al
Proc. IEEE (2007)

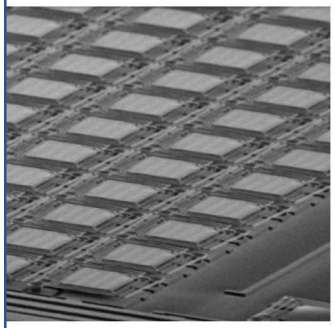
Existing uncooled THz detector technology

Can we make something like this?



- Non-planar
- Flexible
- Room temperature
- No antenna
- Unpowered

➢ Inkjet printing of nanomaterials



Rigid
Planar
Complex fab
Monolithic
Antenna
Powered

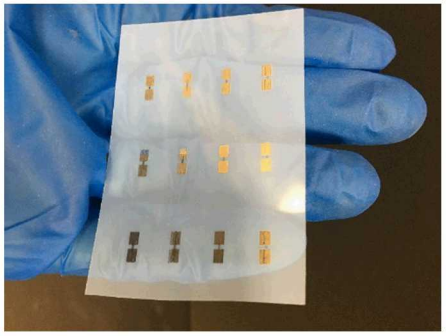
Detector type
Golay cell
Piezoelectric
VO_x microbolom
Bi microbolomete
Nb microbolomet
Ti microbolomete
Ni microbolomete
Schottky diodes
Schottky diode (z
Mott diodes
Si MOSFET
Si FET
Si CMOS
SiN membrane
Micro-Golay cell
HgCdTe HEB

Rogalski & Sizov, Optoelectronics Review (2011).

Unique challenges for inkjet printed THz detectors

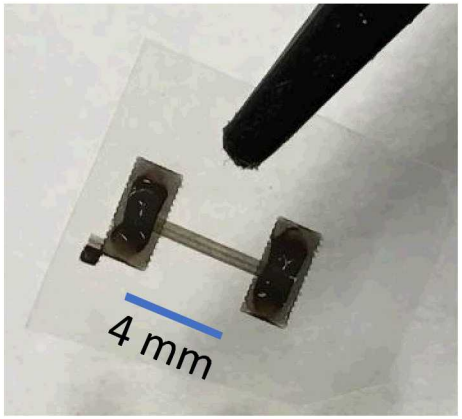
- Printed active material must absorb as much THz as possible
  - Requires thick films, not typical for inkjet printing of active devices
- Device must generate photocurrent
  - Requires p-type and/or n-type inks
- Inks must be stable and printable
- Substrate compatibility for printing
- Devices must be stable to environment

Fuji Dimatix Inkjet Printer



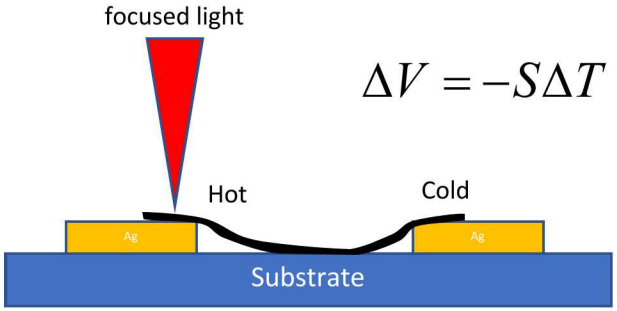
Previously

substrate 110um PET



$$THz\ NEP = \frac{noise}{responsivity} \sim 150\ \mathrm{nW}/\sqrt{Hz}$$

Photothermoelectric



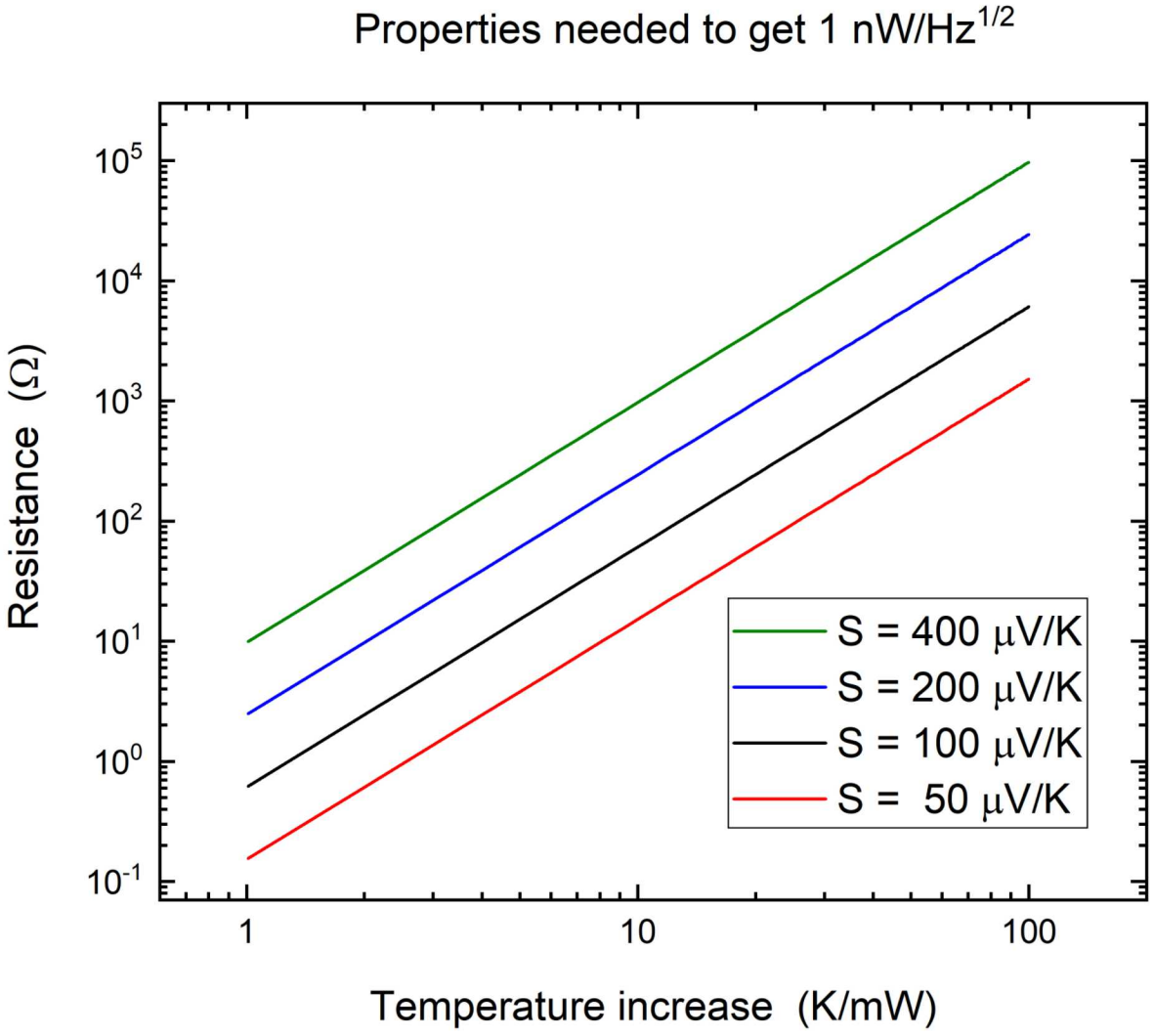
$$\Delta V = -S\Delta T$$

How to improve performance?

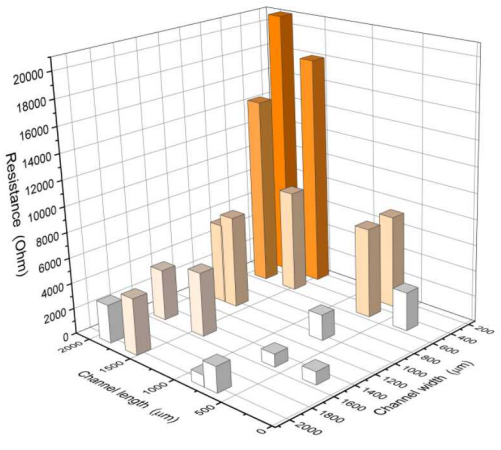
-Materials
-Substrate
-Doping
-Geometry

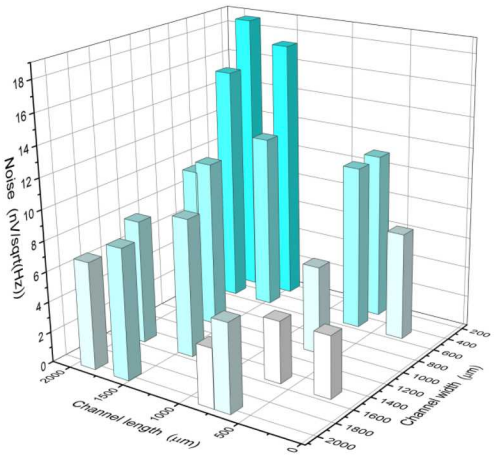
How to get to 3D?

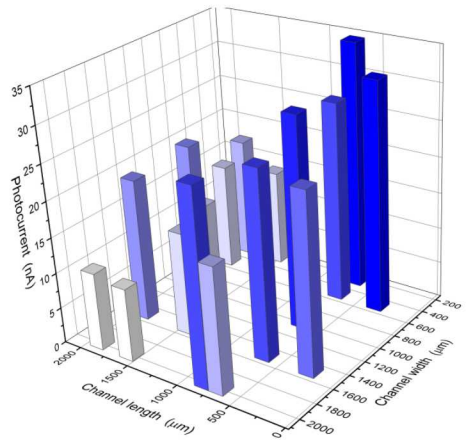
-Ultraflexible
-Architecture

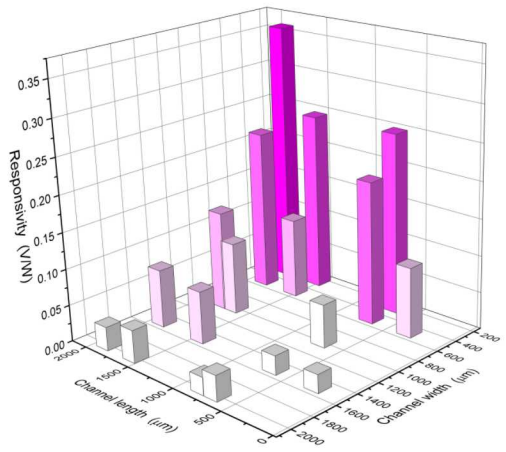

Properties needed to get 1 nW/Hz^1/2
Resistance (Ω)
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
1
10
100
Temperature increase (K/mW)
S = 400 μV/K
S = 200 μV/K
S = 100 μV/K
S = 50 μV/K

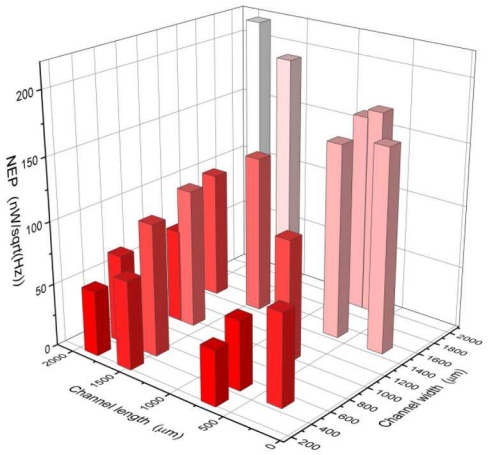
Optimizing pixel geometry











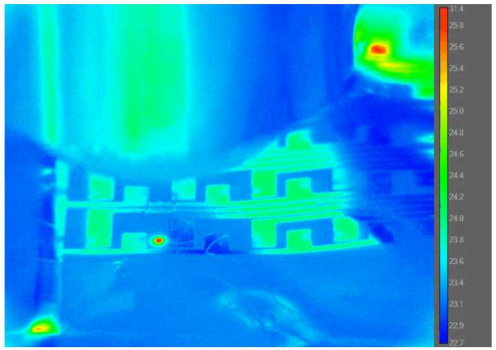
-110 μm PET substrate

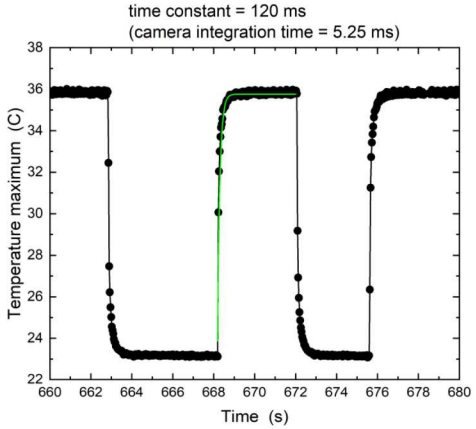
-Unwashed semiconducting+metal CNTs

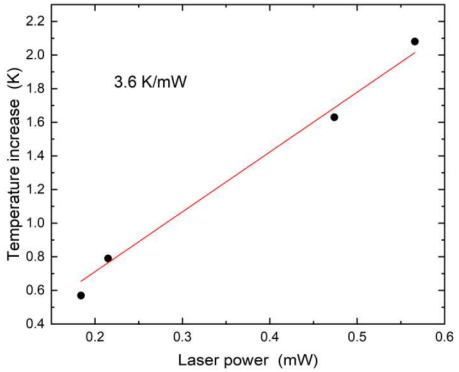
Temperature Increase and Substrate

-110 µm PET substrate
-Unwashed semiconducting+metal CNTs

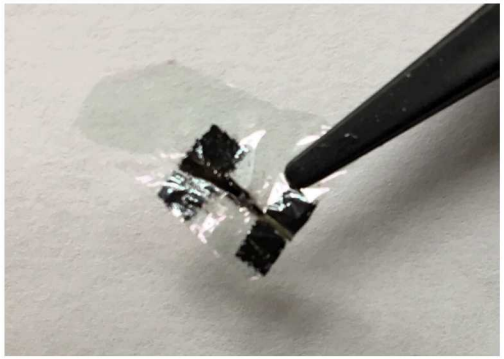
focused green laser







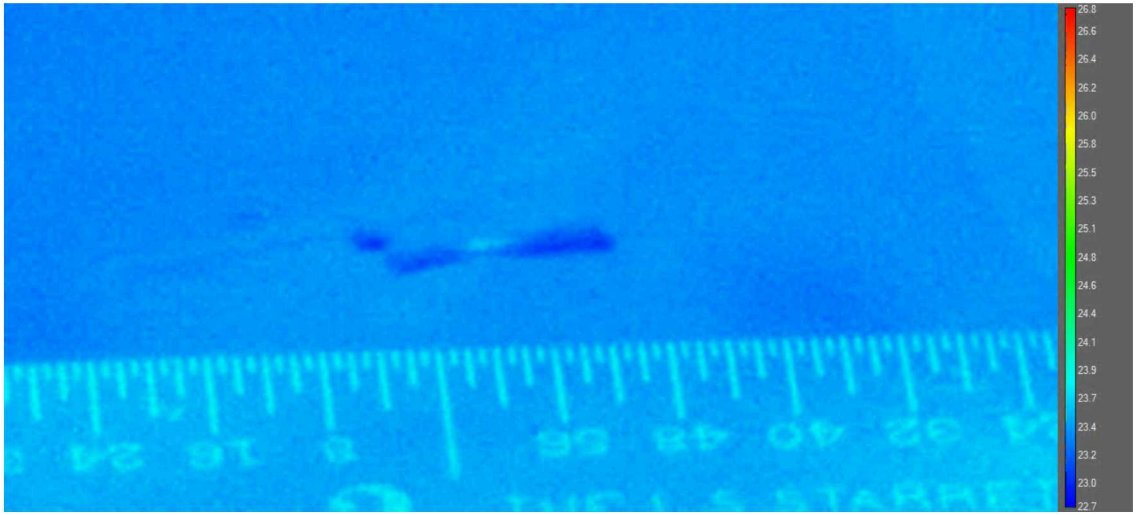
- Small temperature increase and slow
- Solution: ultrathin substrate

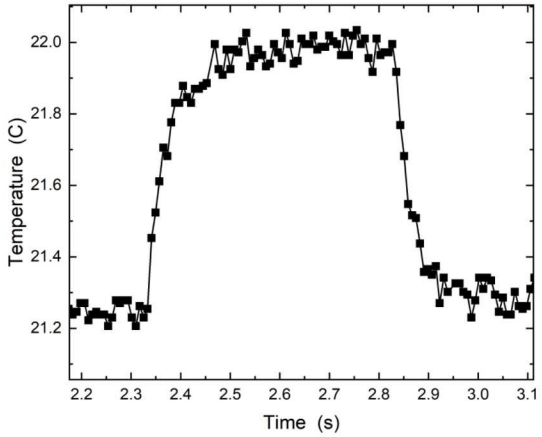


Substrate 0.9µm PET

Up to 17K/mW!

Observation of heating by THz beam



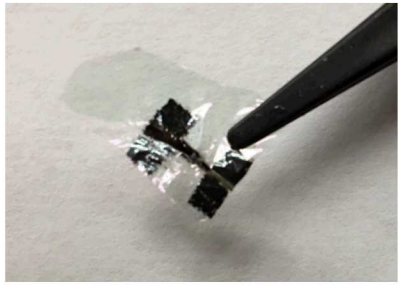


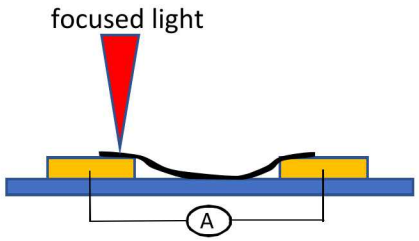
response time = 39 ms

- Larger temperature increase and faster response

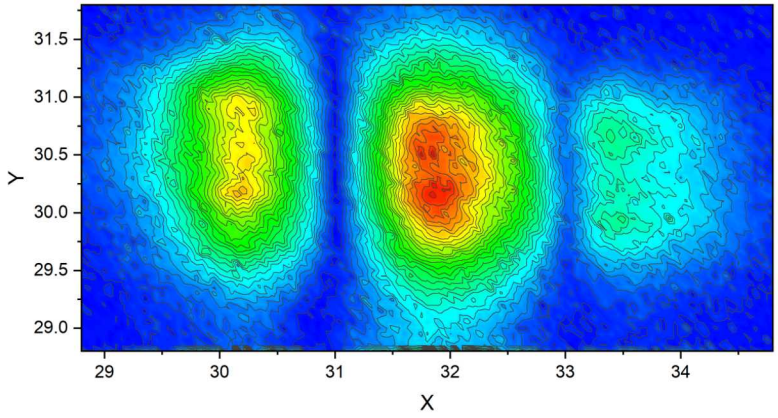
Materials and Doping

Semi+metallic CNTs
0.9um PET
PVP doping





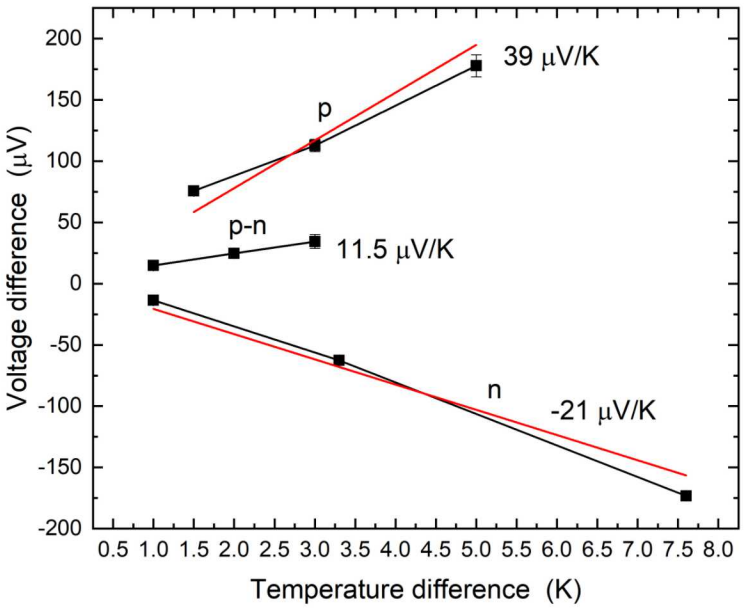
Scanning Photocurrent Image in THz



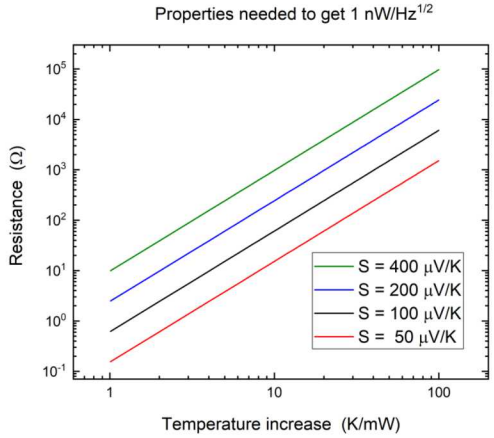
$$THz\ NEP = \frac{noise}{responsivity} \sim 30\ \mathrm{nW}/\sqrt{Hz}$$

Materials and Doping

Thermoelectric measurements
Semi+metallic CNTs



Resistance ~ a few kΩ at best

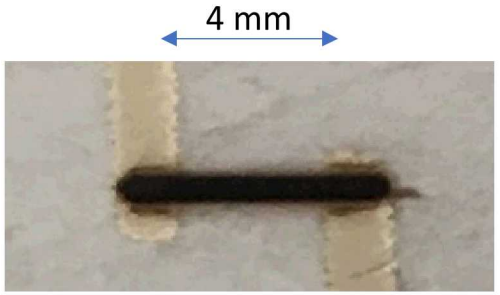


- Seebeck too low
- Resistance too high
- Solutions: semiconducting CNTs and removal of surfactants

Materials and Doping

- Surfactant removal:

  -Problem that we need surfactant for n-type
  -Focus on p-type homojunctions



- Semiconductor-rich CNTs (99% Nanointegris)

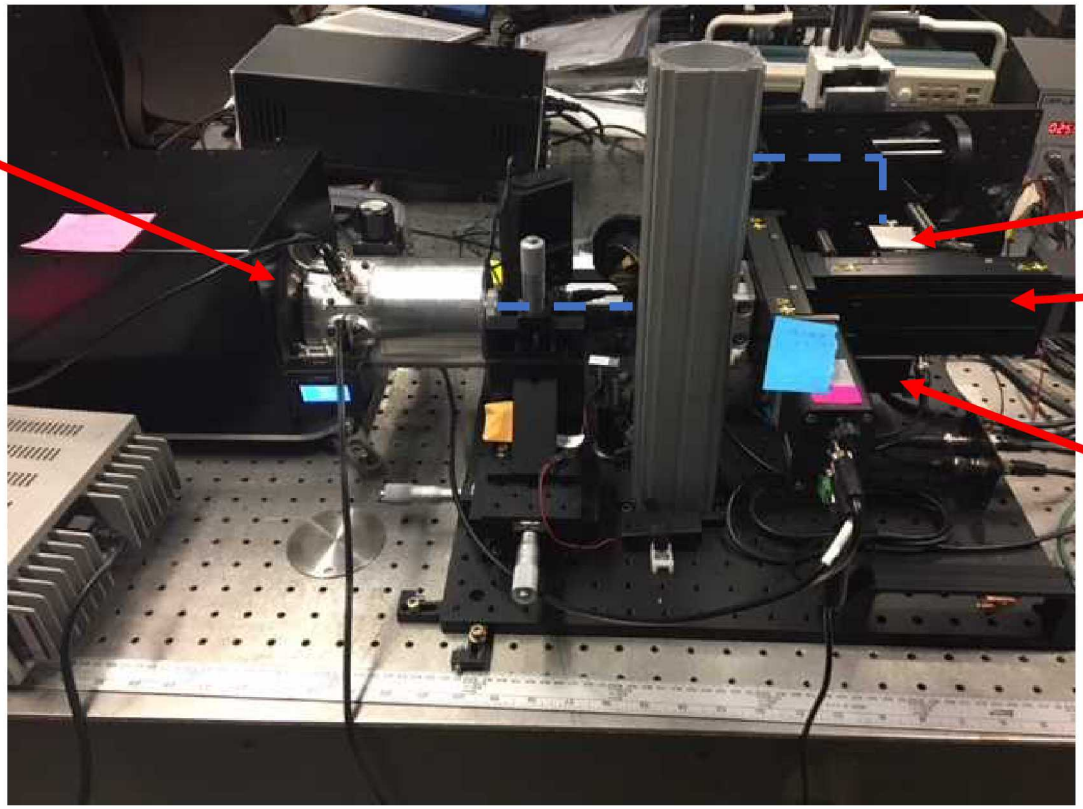
$$Green\ NEP = \frac{noise}{responsivity} \sim 18\ \mathrm{nW}/\sqrt{Hz}$$

- Wash devices with DI water

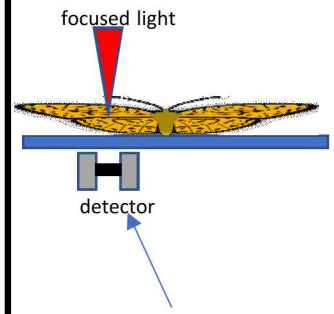
$$Green\ NEP = \frac{noise}{responsivity} \sim 2\ \mathrm{nW}/\sqrt{Hz}$$

$$THz\ NEP = \frac{noise}{responsivity} \sim 25\ \mathrm{nW}/\sqrt{Hz}$$

THz imaging

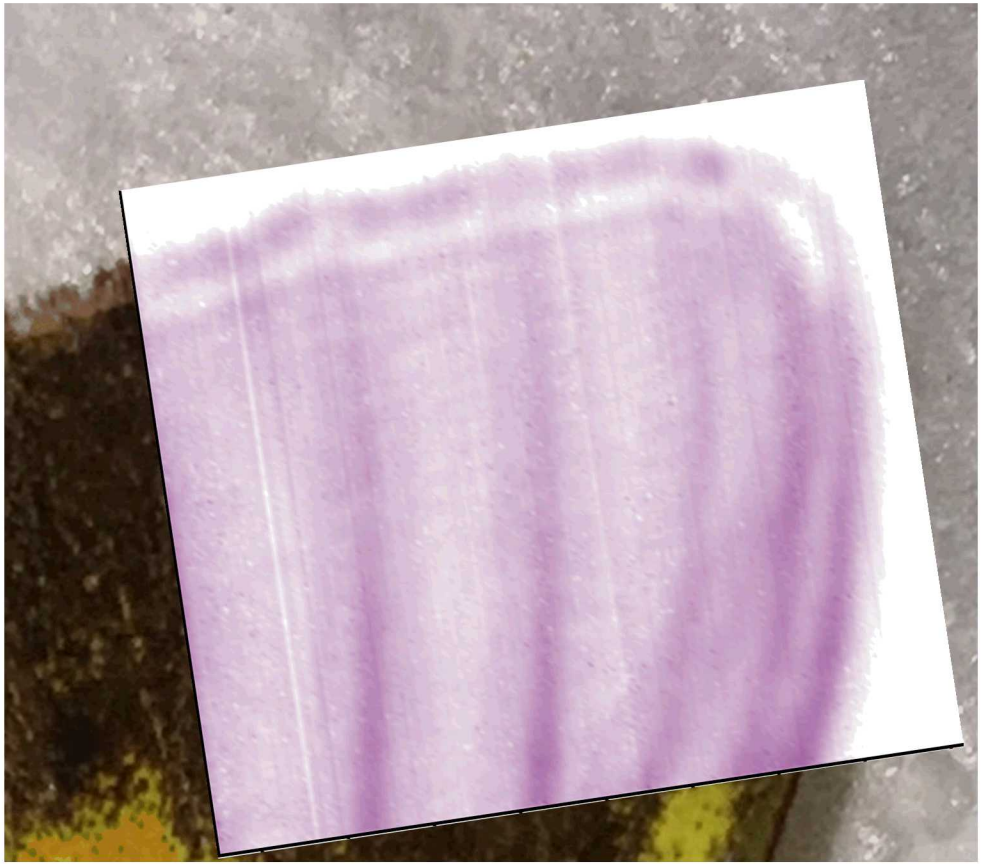

THz beam path
QC
Laser
Frequency: 2.9THz to 3.8THz
Wavelength: about 100um
Power: up to 7mW
sample
Scanning
stage
detector

THz imaging using inkjet printed CNT detector

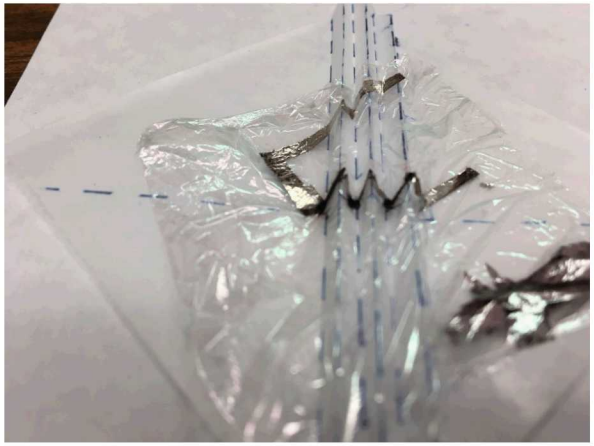


Using our inkjet printed detector!

Colias croceus (clouded yellow)

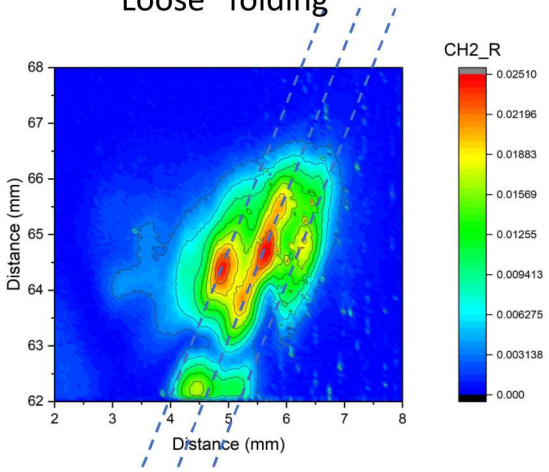


Origami detector

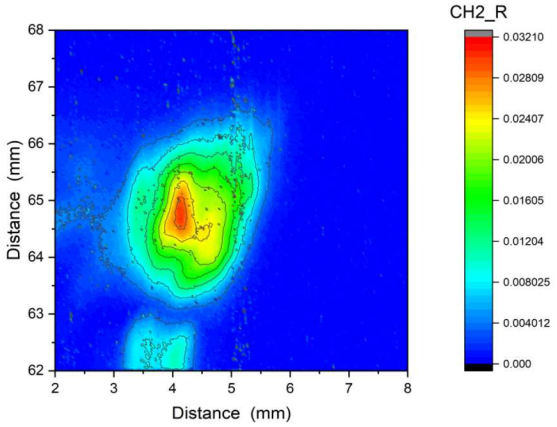


Origami detector

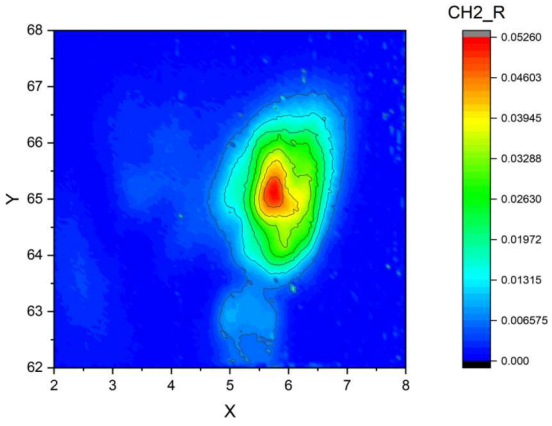
"Loose" folding



"Medium" folding



"Tight" folding

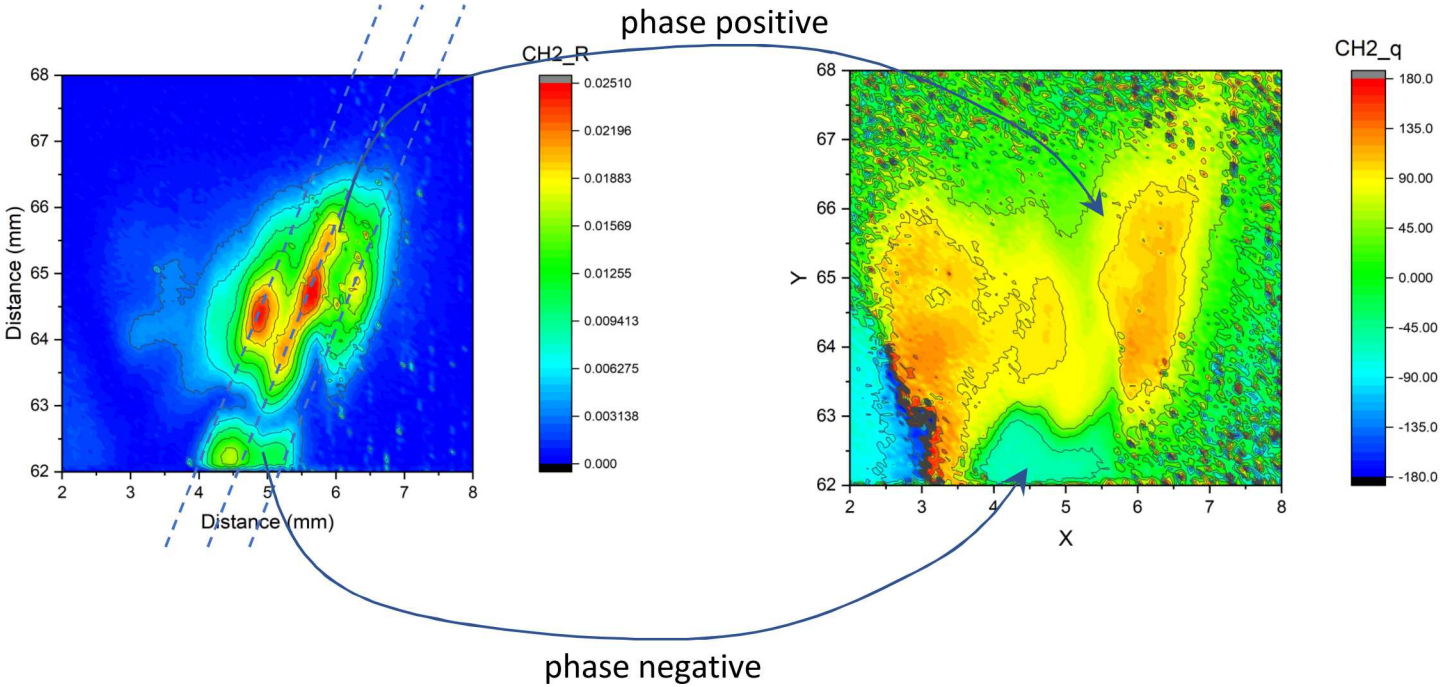


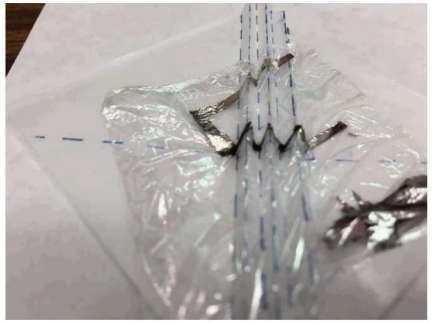
-Three peaks
-Photocurrent amplitude = 0.025

-Two peaks
-Photocurrent amplitude = 0.032

-One peak
-Photocurrent amplitude = 0.052

Origami detector



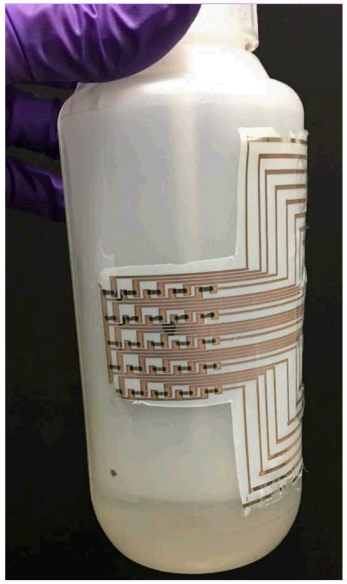


Advantage of origami detector:

The two opposite responses are spatially offset

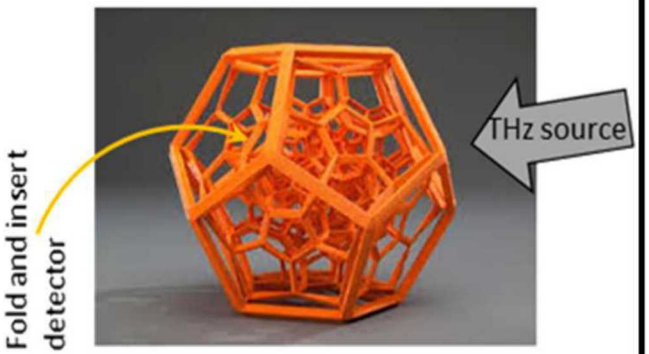
Future

Non-planar, flexible imaging array



Ultraflexible, embedded, state-of-health sensors

Insertable, deployable sensors



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