Figure of Merit for Carbon Nanotube Photothermoelectric Detectors

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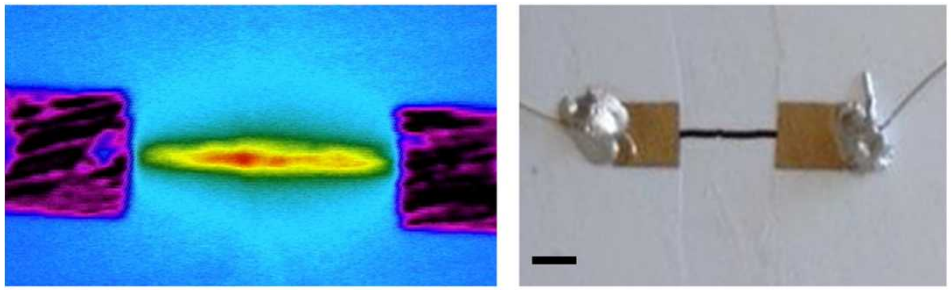
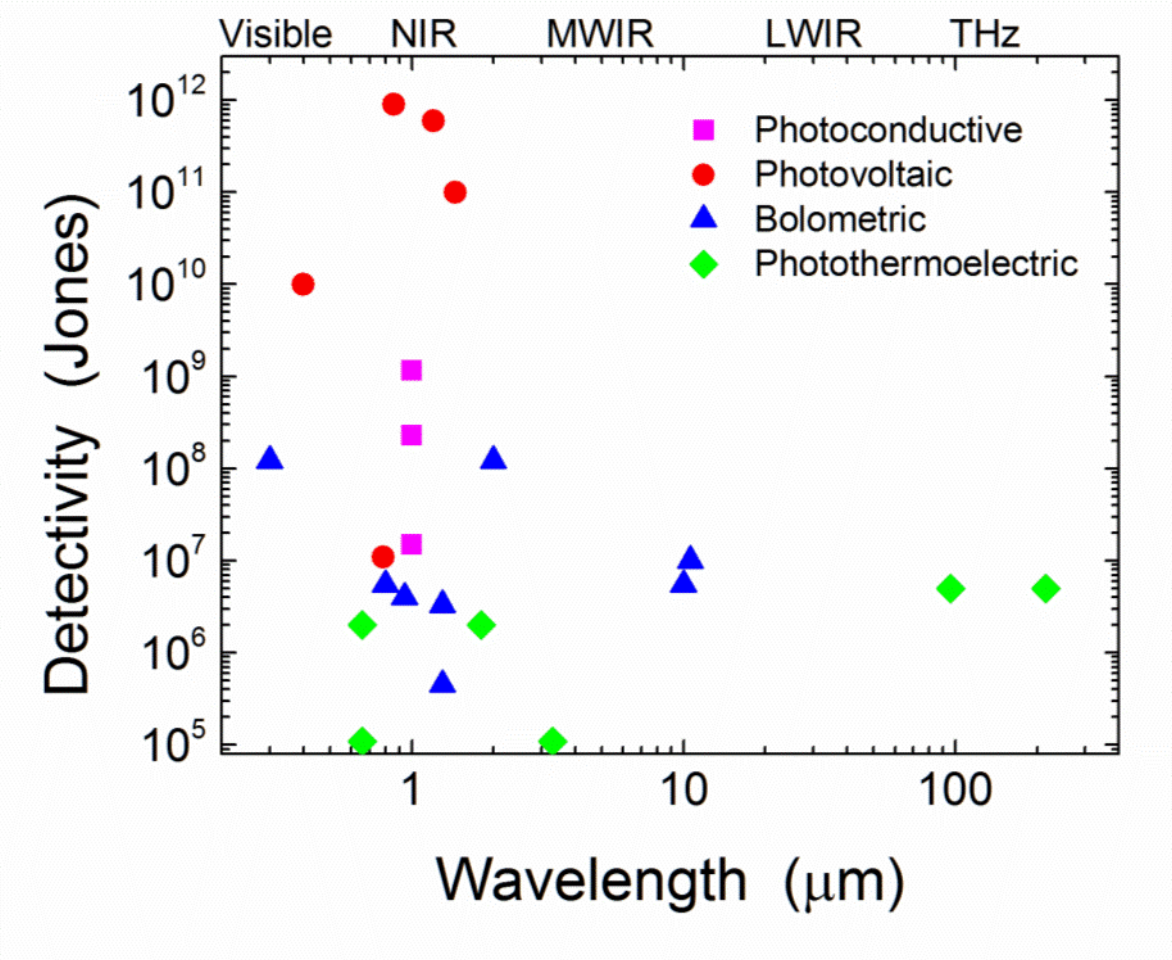


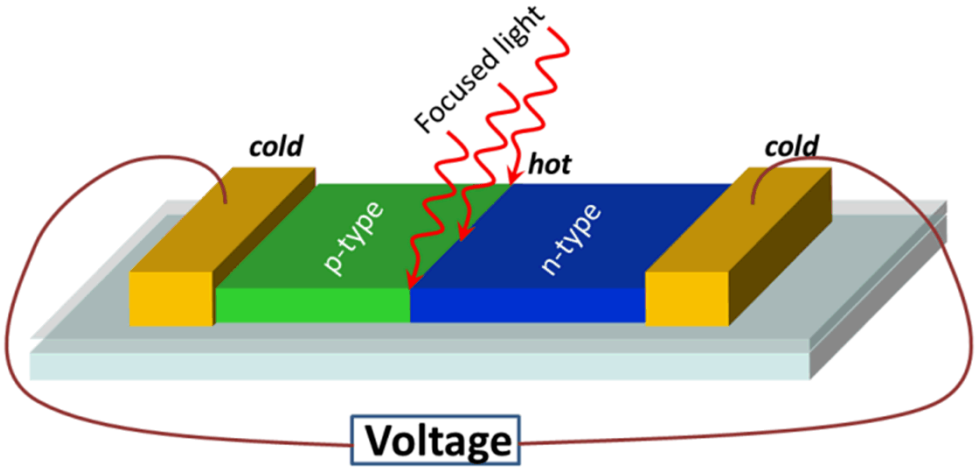
Erickson et al, *ACS Nano* **9**, 11618 (2015).

Previous work on CNT photodetectors



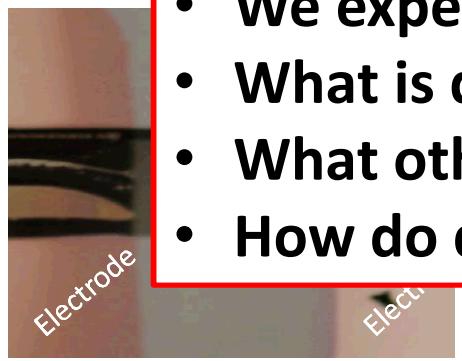
X. He, F. Léonard, J. Kono, *Advanced Optical Materials (2015)*.

Photothermoelectric detectors



$$\Delta V = S_p \Delta T_p - S_n \Delta T_n = (S_p - S_n)\Delta T$$

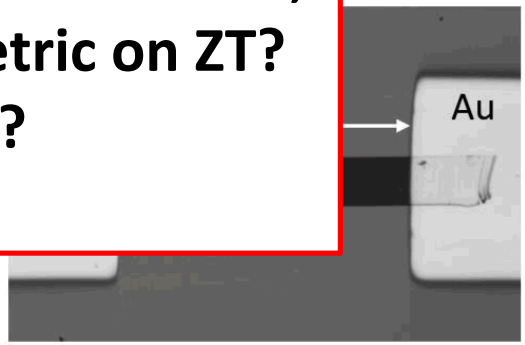
- **We expect the ZT factor to determine performance;**
- **What is dependence of performance metric on ZT?**
- **What other factors govern performance?**
- **How do different devices compare?**



0.5 mm

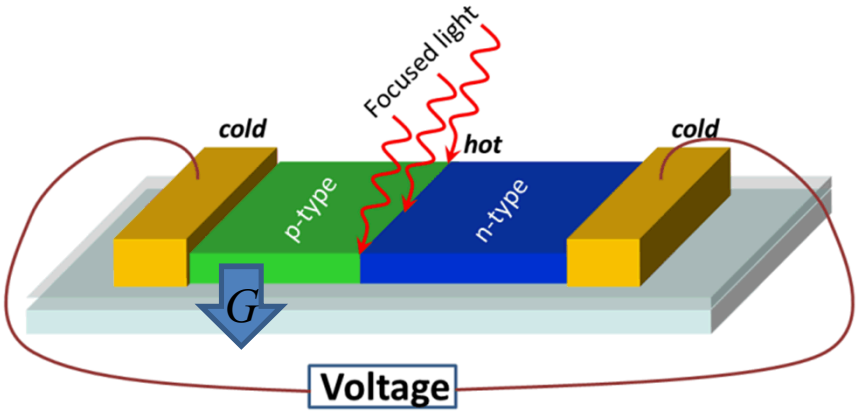
Scientific Reports (2013)

ACS Nano (2013)



Nano Letters (2014)

Responsivity



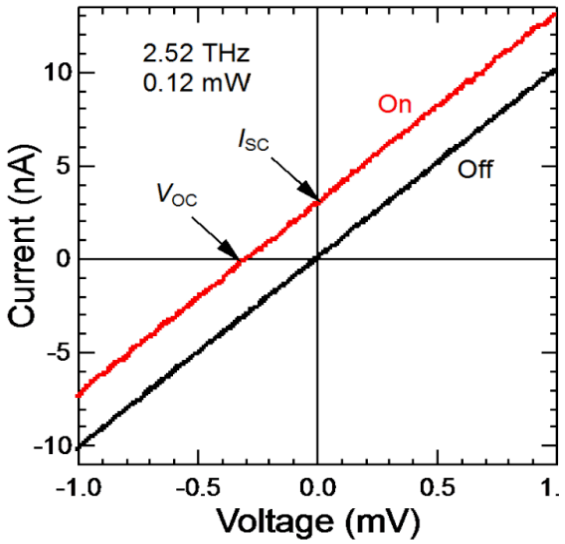
$$\Delta V = (S_p - S_n)\Delta T$$

$$\mathcal{R} = \frac{Photovoltage}{Optical\ Power} = \frac{\left(S_p - S_n\right)\Delta T}{P}$$

$$\Delta T_{\max} = \frac{P}{W\sqrt{\kappa h G}}$$

Noise Equivalent Power

$$NEP = \frac{noise\ spectrum}{responsivity}$$



A photothermoelectric detector generates a signal at zero bias

thermal noise $\sqrt{4k_B TR}$

$$NEP = \frac{2\sqrt{k_B T^2 WL}\sqrt{G}}{\sqrt{ZT}}$$

$$ZT = \frac{S^2 \sigma T}{\kappa}$$

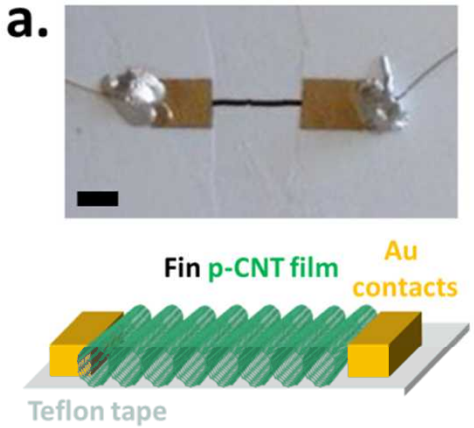
Approach

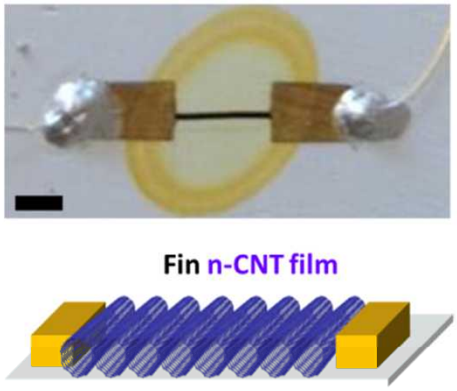
$$NEP = \frac{noise\ spectrum}{responsivity}$$

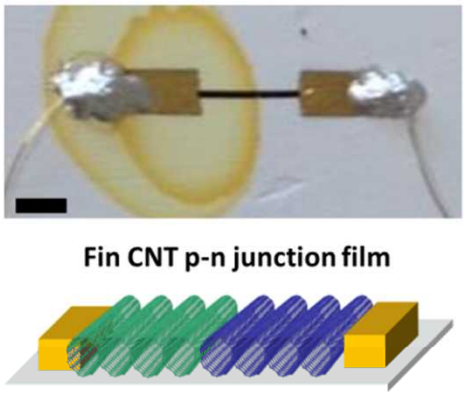
$$NEP = \frac{2\sqrt{k_B T^2 WL}\sqrt{G}}{\sqrt{ZT}}$$

$$ZT = \frac{S^2 \sigma T}{\kappa}$$

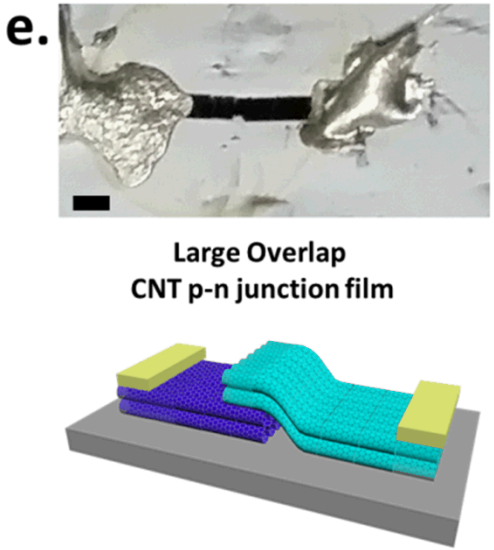
Several Devices Tested

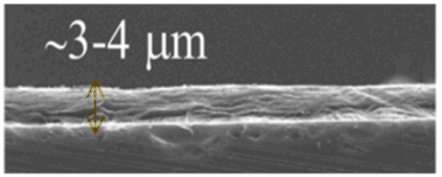


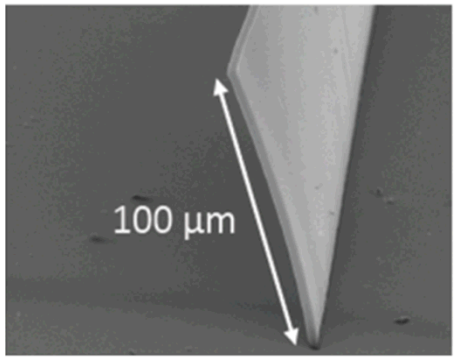




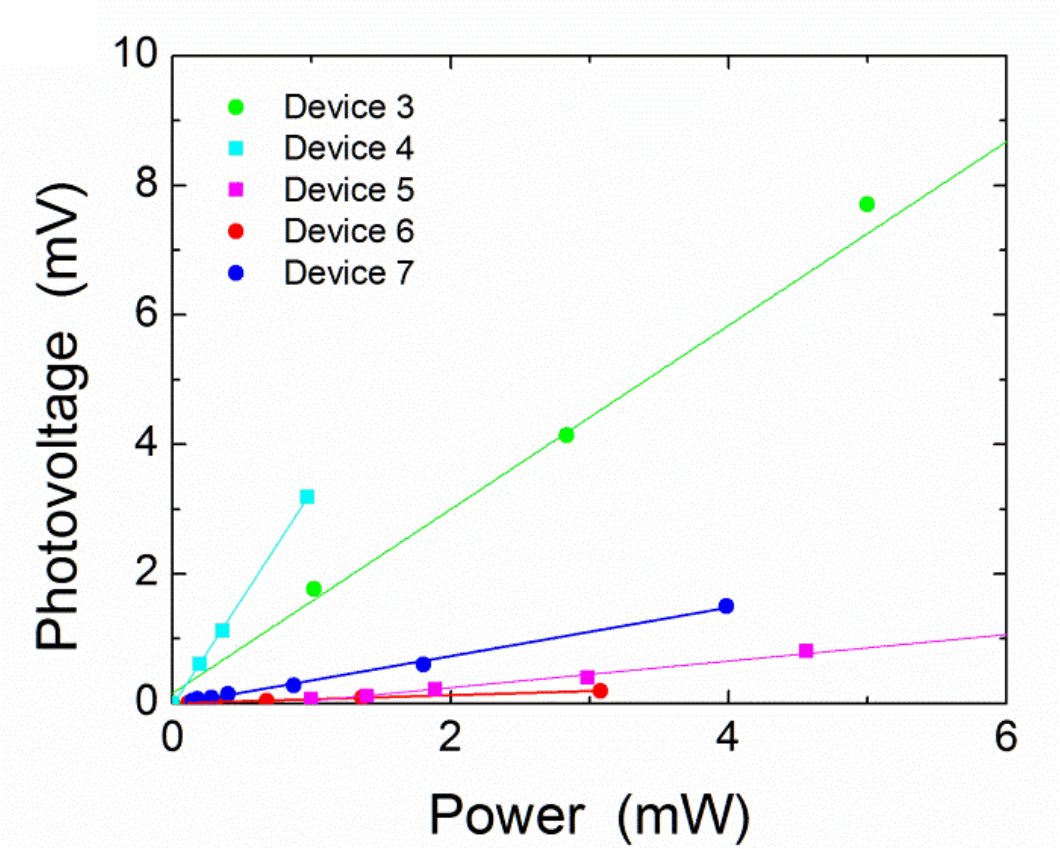
3 of these on different substrates







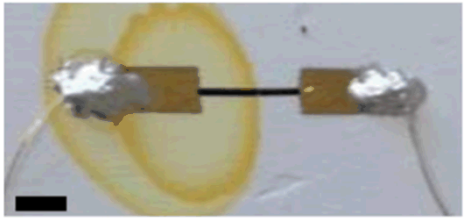
Responsivity



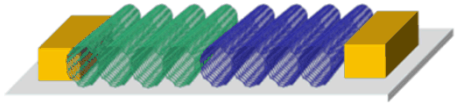
➢ **Device 4 should be the best, right ??**

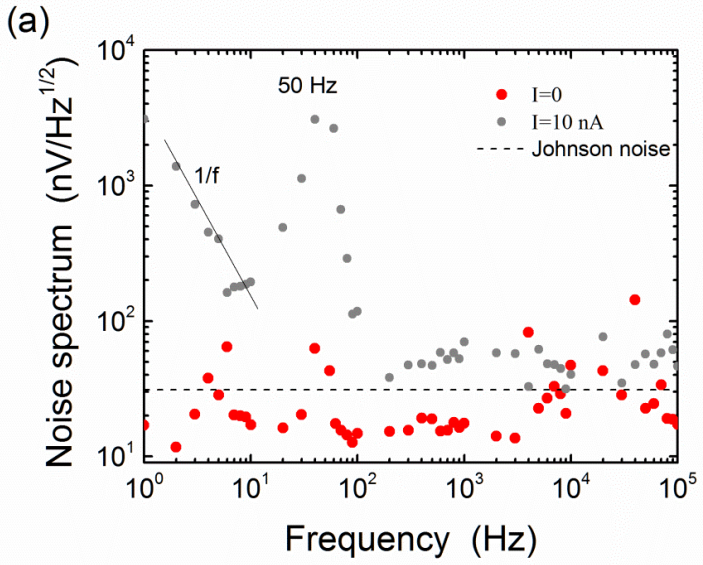
Small Overlap
CNT p-n junction film

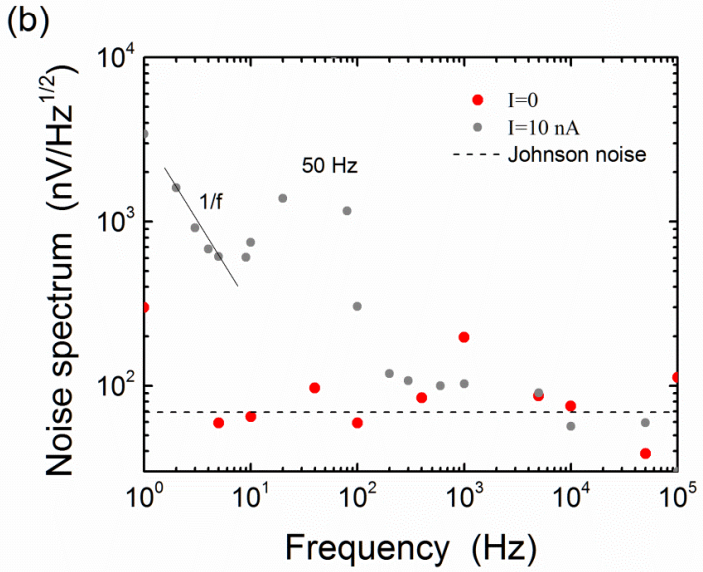
Noise Measurements



Fin CNT p-n junction film

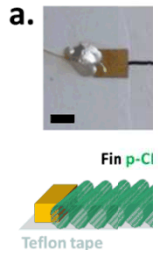


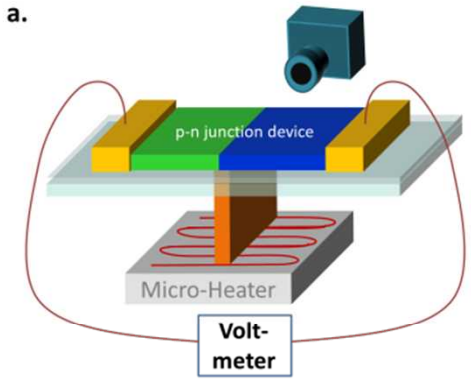


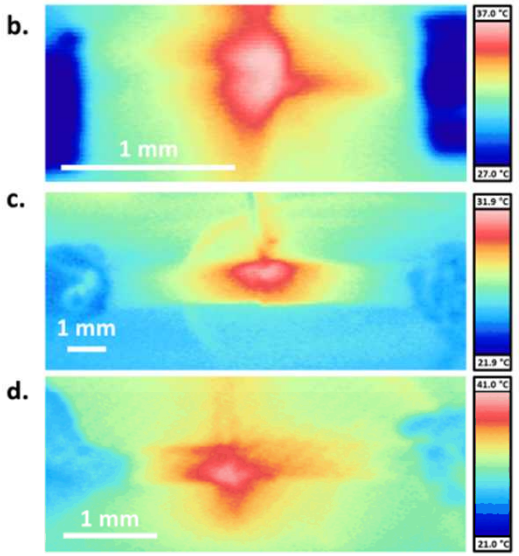


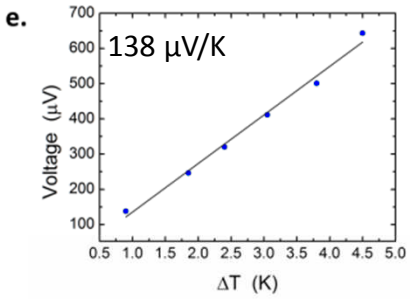
thermal noise
at zero bias

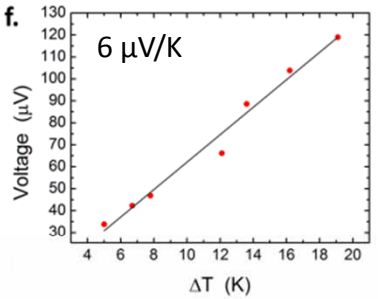
Seebeck Coefficient

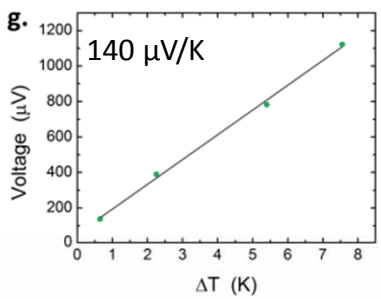


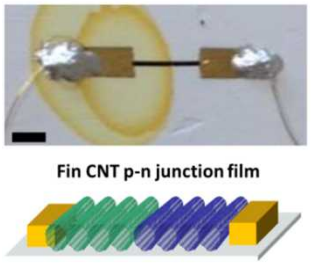


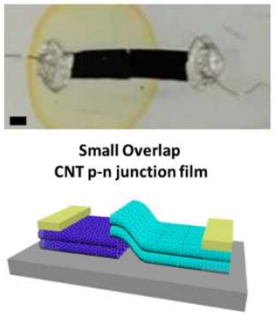


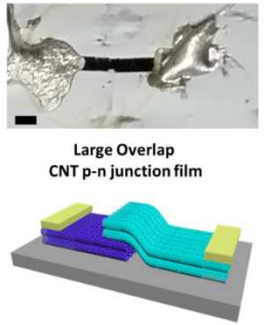




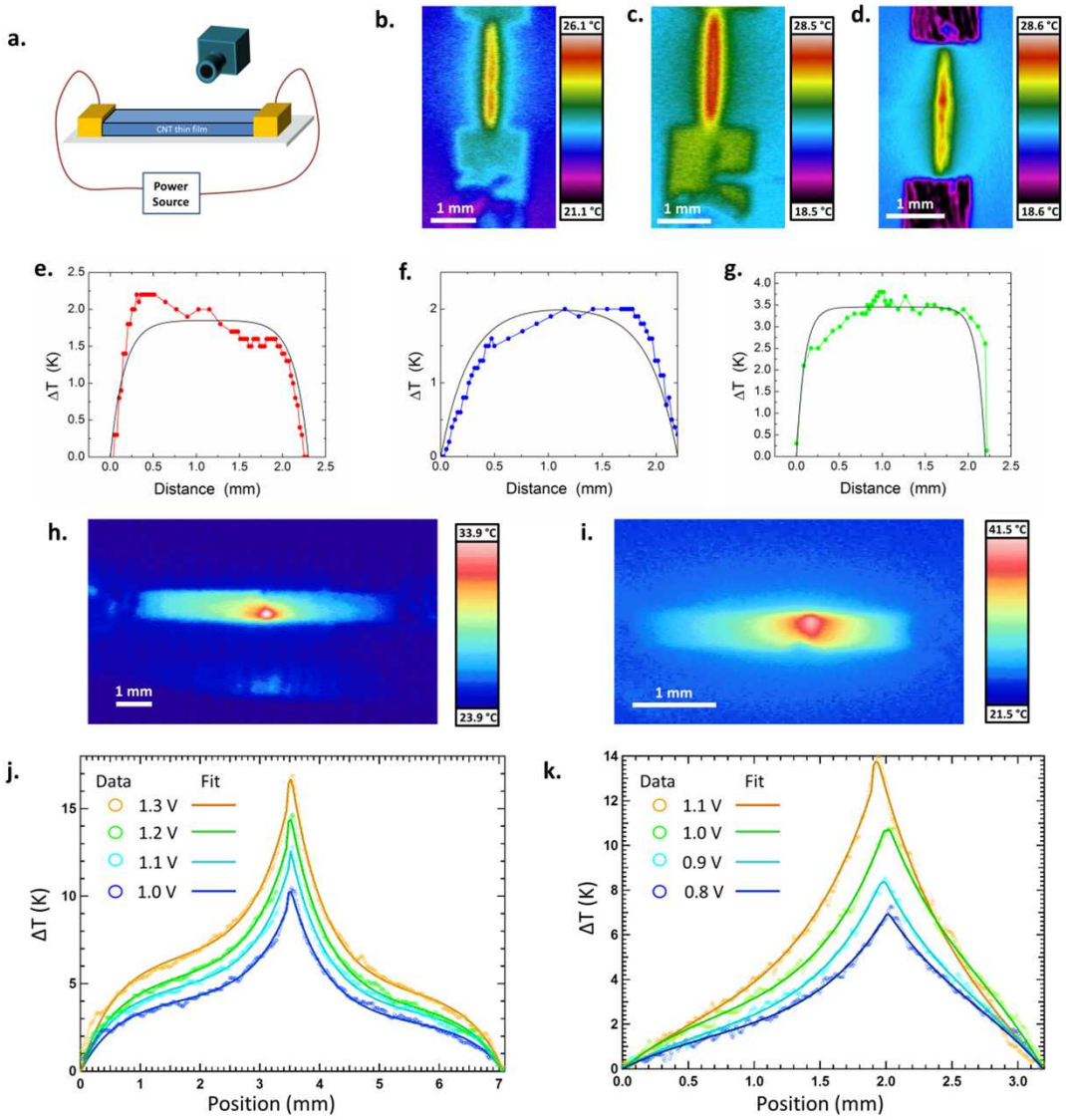




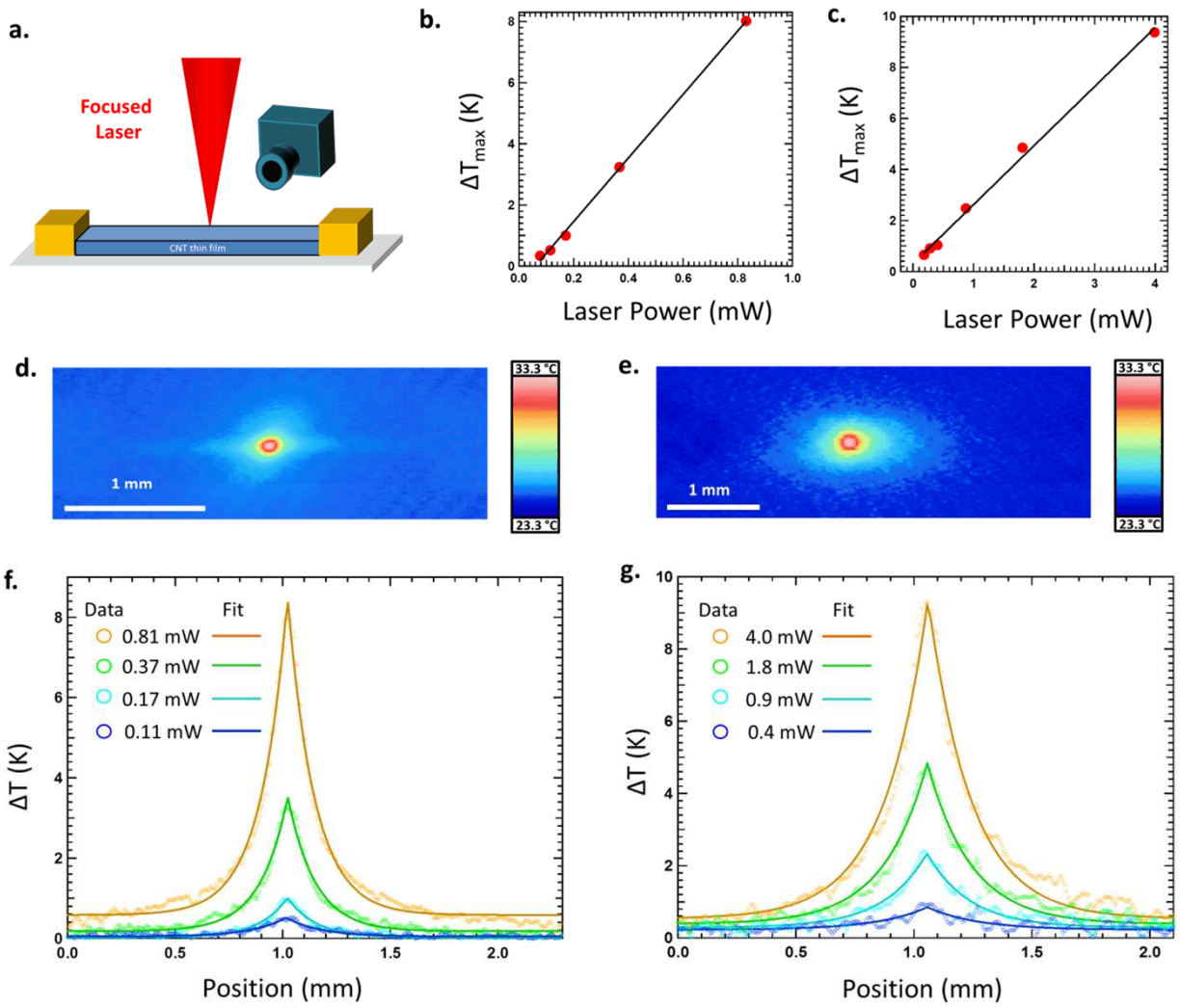




Joule Heating to obtain κ and G



Optothermal measurements to obtain κ and G



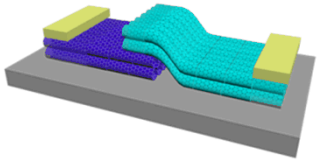
Note: this is also used to verify device Seebeck coefficient

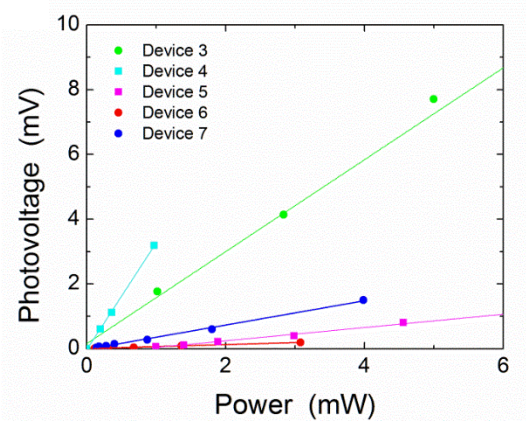
Prospects for Improvement

Device	ZT	Resistance	NEP direct ($nW/Hz^{1/2}$)	NEP from components ($nW/Hz^{1/2}$)
3, suspended	1.5e-5	100 kΩ	25	23
4, Teflon on AlN	1.0e-5	56 kΩ	23	23
5, AlN	1.2e-5	280 kΩ	418	383
6, suspended	1.2e-5	146 Ω	26	24
7,suspended	1.8e-4	287 Ω	6	7

Champion:

Large Overlap
CNT p-n junction film





Prospects for Improvement

$$NEP = \frac{2\sqrt{k_B T^2 WL}\sqrt{G}}{\sqrt{ZT}}$$

ZT ~ 0.05, Avery et al, Nature Energy (2016) ⟹ factor of 10

G at the radiation limit ⟹ factor of 10

Summary

- Explicit expression for photodetector performance;
- Good agreement between device and materials approaches;
- Best devices don't necesseraly have largest responsivity;
- Provides a path for technology development.

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