Nanoscale thermal characterization and solid-state heat management

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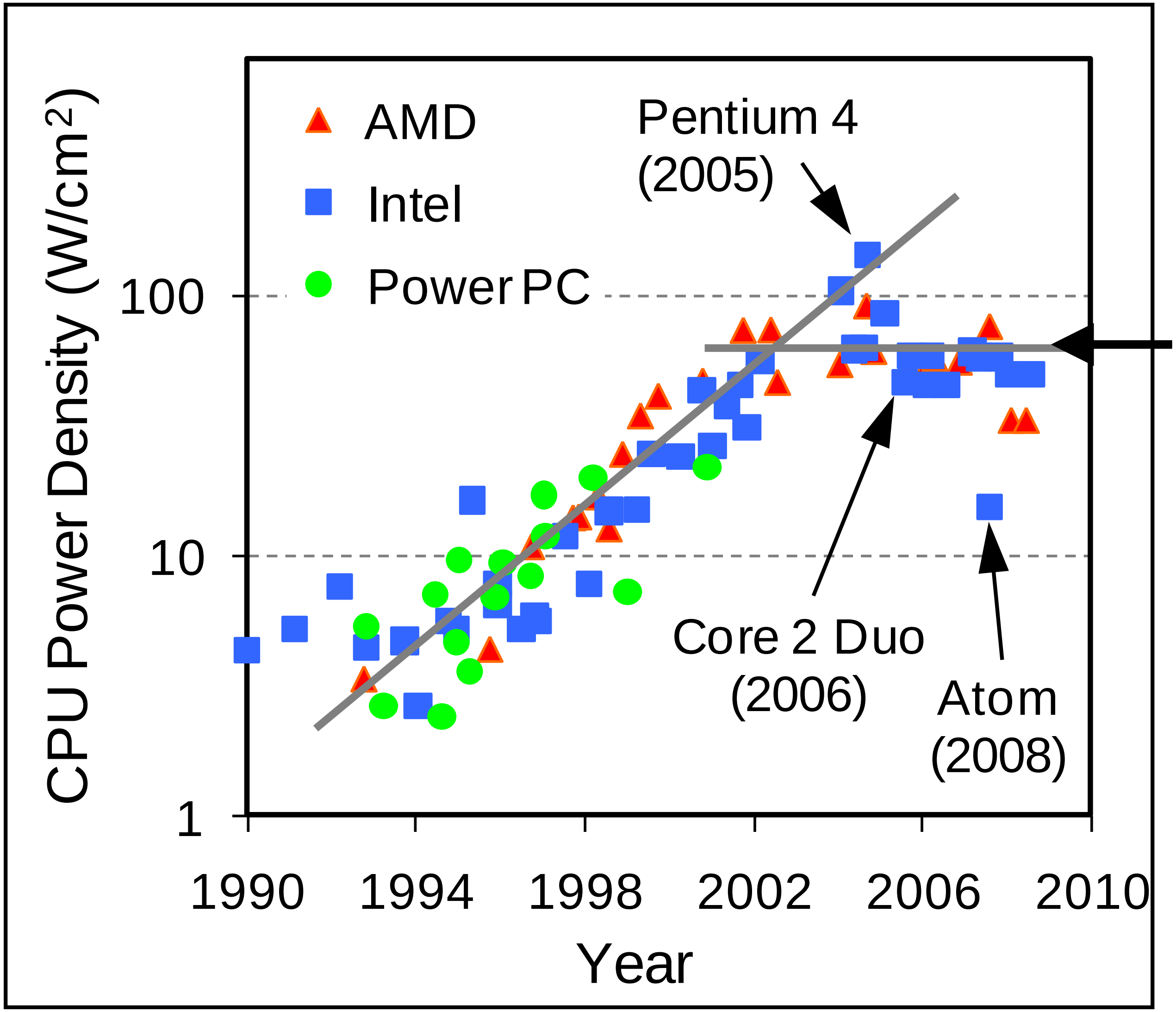
CSIC

ESMolNa, Santa Pola, 20th May 2025

2D FOUNDRY

erc
European Research Council
Established by the European Commission

Motivation

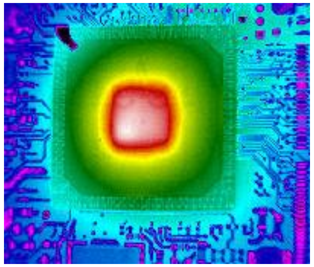


Electronics, limited by power & heat since 2005!

* E. Pop, Nano Research, 3, 147-169 (2010)

Heat dissipation in electronics

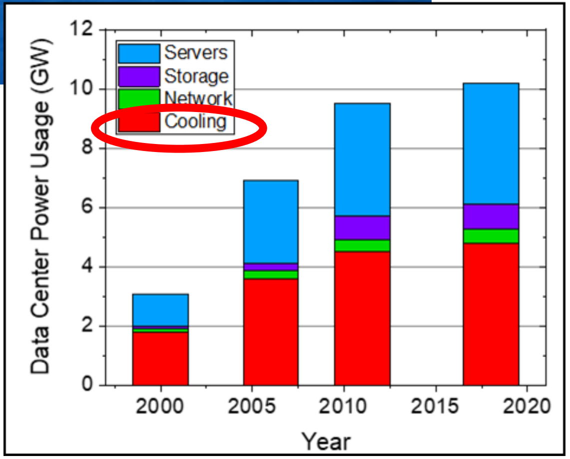
Devices



Wasted heat

http://www.phys.ncku.edu.tw/~htsu/humor/fry-egg.htlm

Data centers

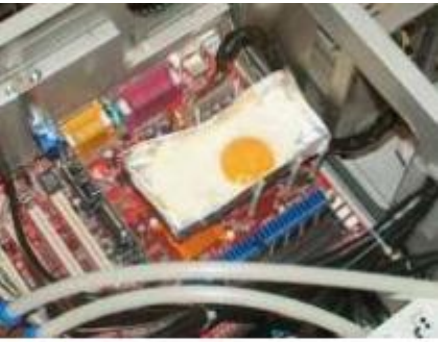


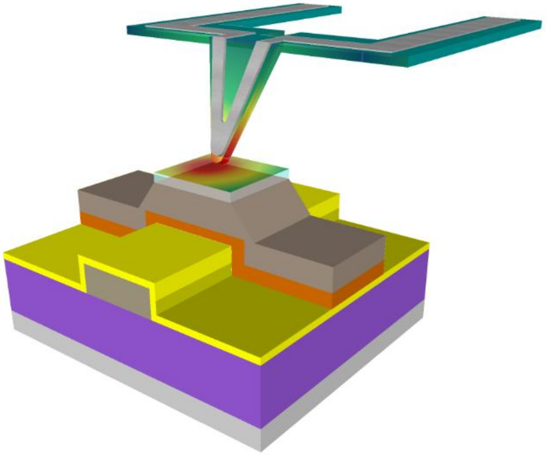
* E. Pop, Nano Research, 3, 147-169 (2010)

- Gaining thermal insights of our electronic devices and learn how to manage this heat is an essential aspect to our electrified future

My research line: Nano- to macro- approach

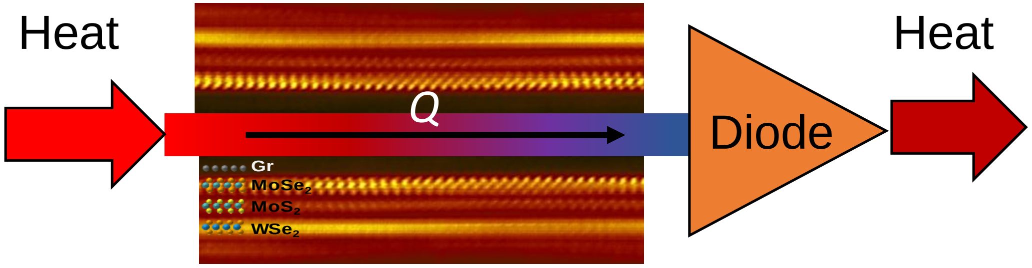
Energy dissipation

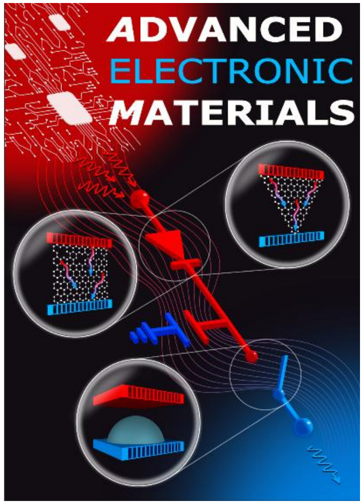




- Nanoscale thermometry

Energy management





ADVANCED
ELECTRONIC
MATERIALS

THALES

VDL ETG Precision

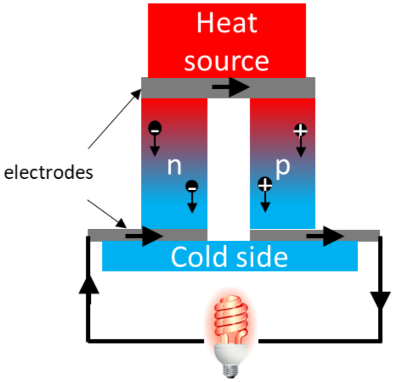
PHILIPS

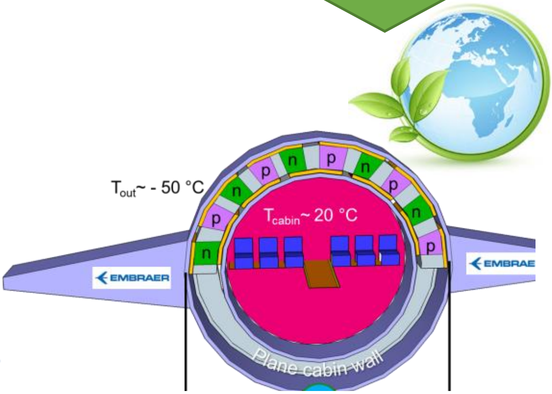
eit InnoEnergy

ASML

- Routing heat
- Active heat control

Energy harvesting





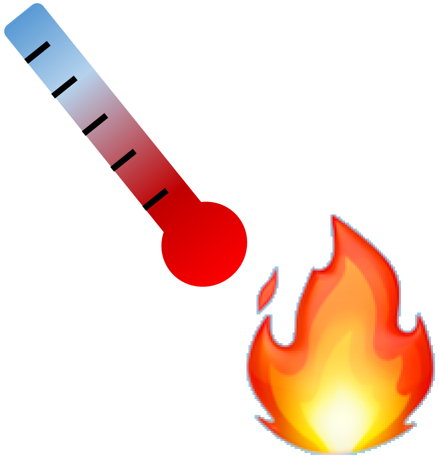
EMBRAER

- Thermoelectrics

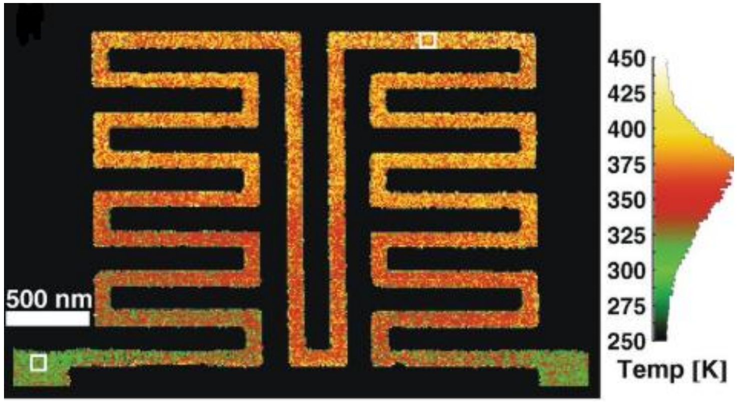
Advanced thermal characterization

How Can We Measure Temperature at Nanoscale?

Thermometer

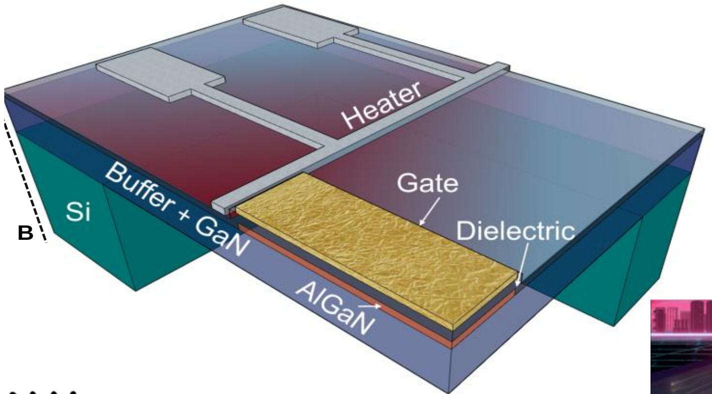


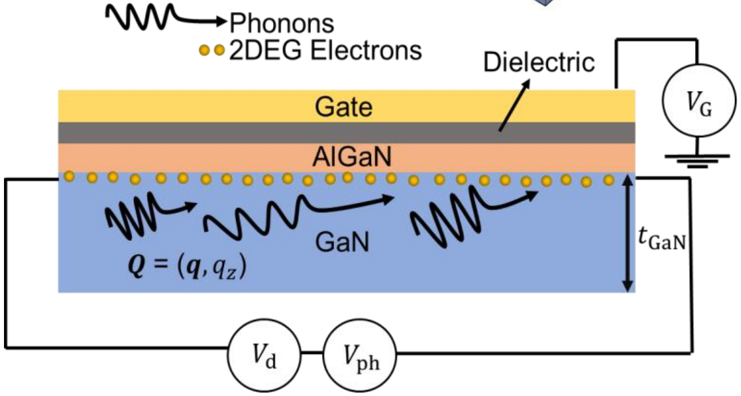
Need for other approaches in the nano- and micro-scale…

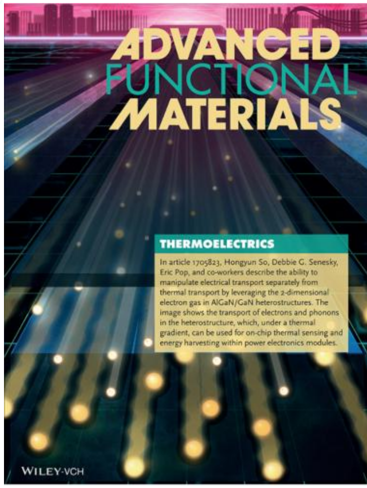


M. Mecklenburg, *et al.*, *Science*, 347, 6222, 2015

Electro-thermal methods







ADVANCED FUNCTIONAL MATERIALS

THERMOELECTRICS

In article 1705823, Hongyun So, Debbie G. Senesky, Eric Pop, and co-workers describe the ability to manipulate electrical transport separately from thermal transport by leveraging the 2-dimensional electron gas in AlGaN/GaN heterostructures. The image shows the transport of electrons and phonons in the heterostructure, which, under a thermal gradient, can be used for on-chip thermal sensing and energy harvesting within power electronics modules.

WILEY-VCH

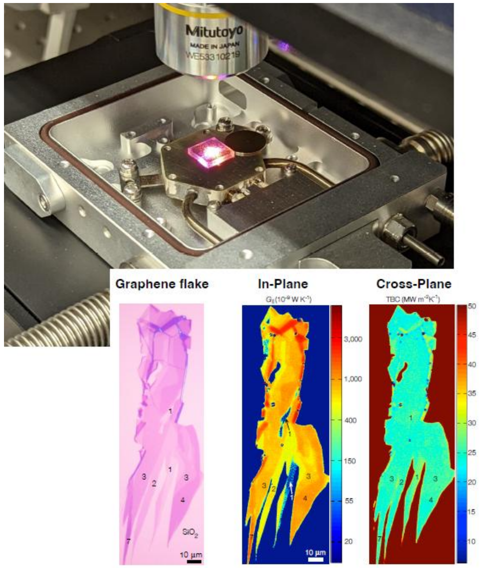
No thermal maps

A.Yalamarthy, **M. Muñoz Rojo**, […] *et al.*, Nano Letters (2019)

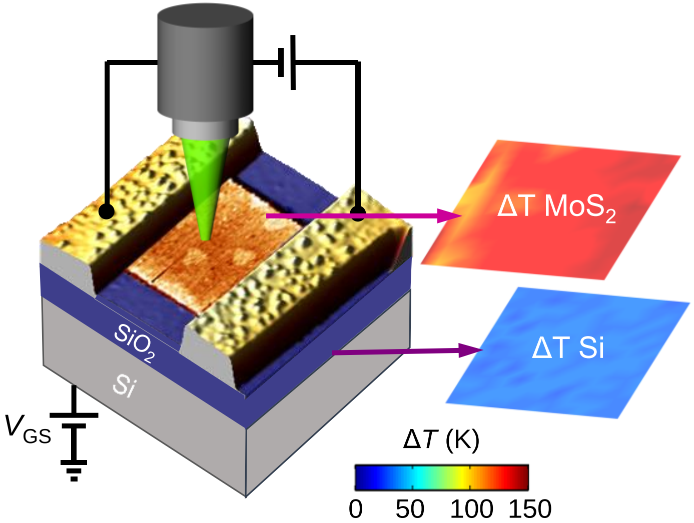
AS Yalamarthy, H So, **M Muñoz Rojo**, […], E. Pop and DG Senesky, *Advanced Functional Materials* 28 (22), 1705823, 2018

Spatially Resolved Device Thermometry

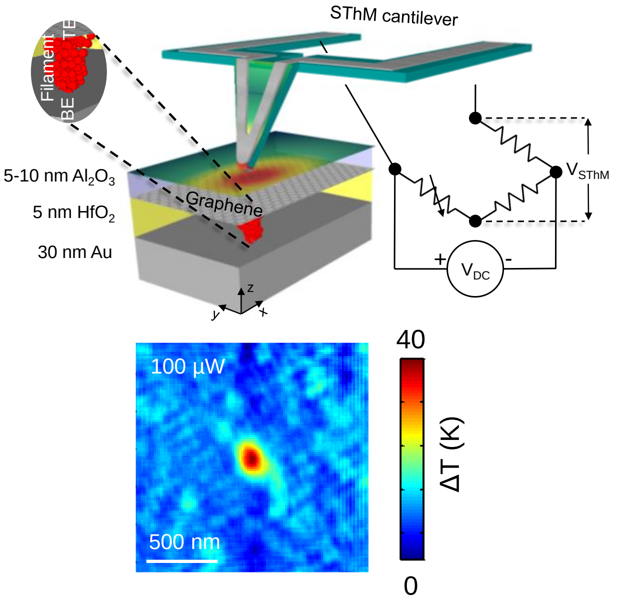
FDTR



Raman



SThM (AFM)



$^+$ Unique SThM calibration approach

~ 2-3 µm ~ 0.5 µm ~ 0.05 µm

Medium-scale T-maps

Material selectivity

High spatial resolution

E. Tornero, […], **M. Muñoz Rojo**, *Submitted* (2025)

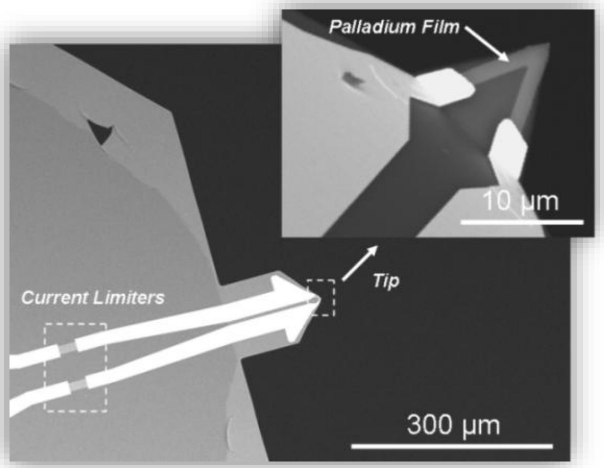
E. Yalon,.., **M. Muñoz Rojo**,.. *et al.*, *Nano Lett.* 17, 3429 (2017)

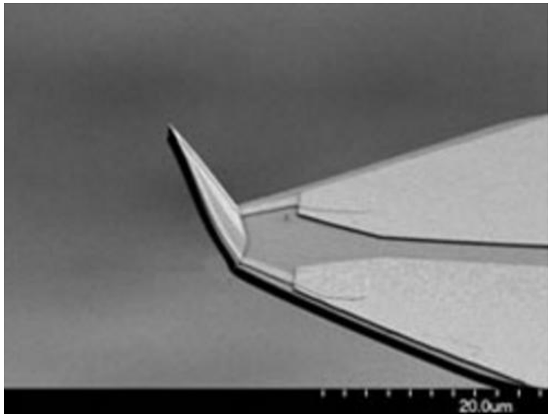
S. Deschmuk*, **M. Muñoz Rojo***, *et al.*, *Science Adv. (2022)*

*Authors contributed equally as first author

SThM thermal mapping

Thermal Probes: Pd/SiN probe





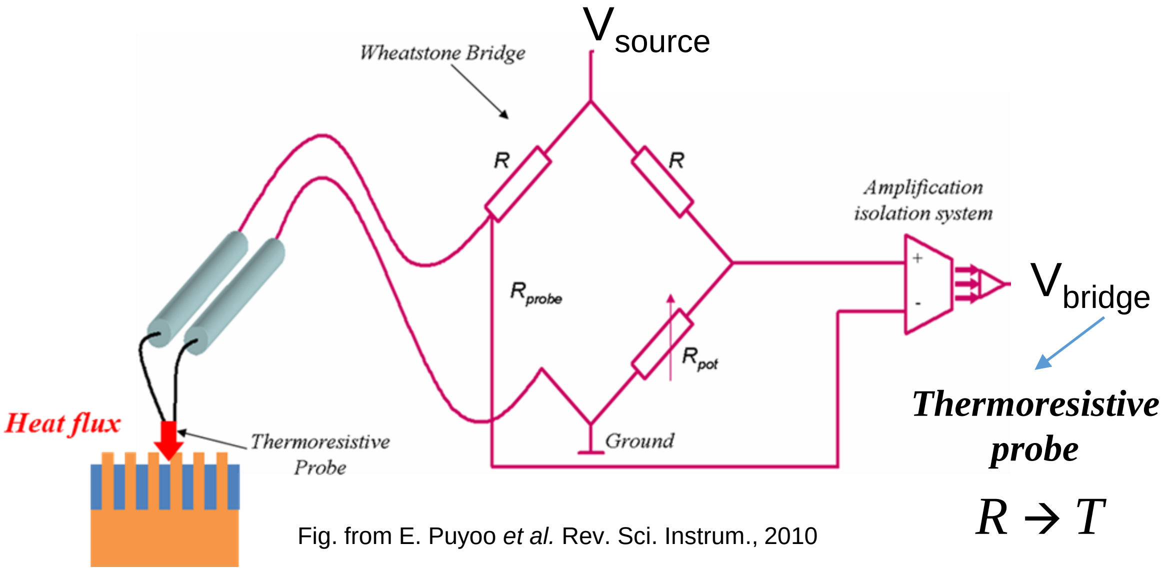
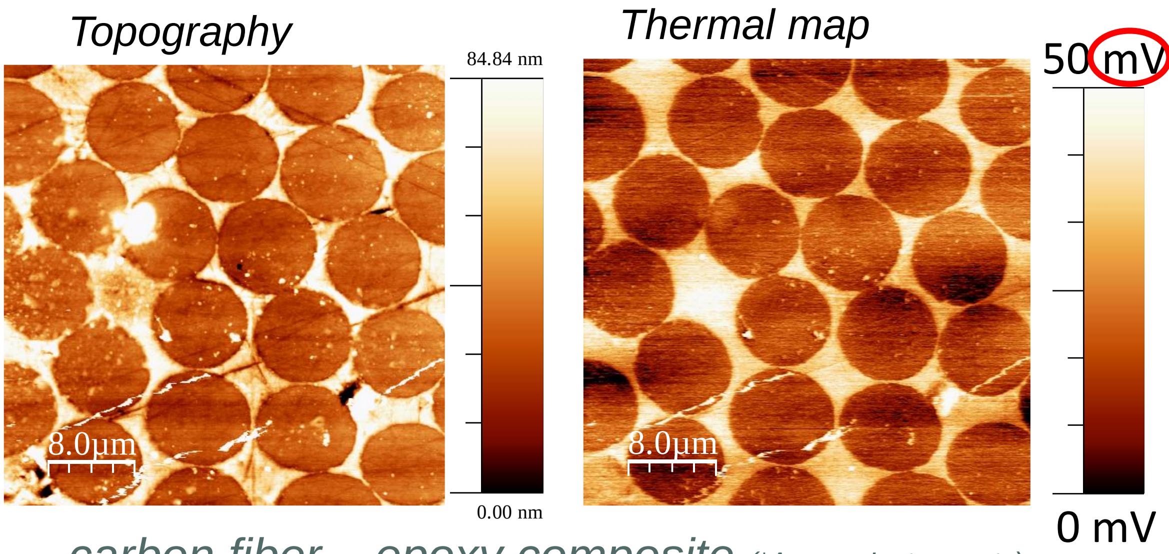


Fig. from E. Puyoo *et al.* Rev. Sci. Instrum., 2010

Thermoresistive probe

R → *T*


Topography

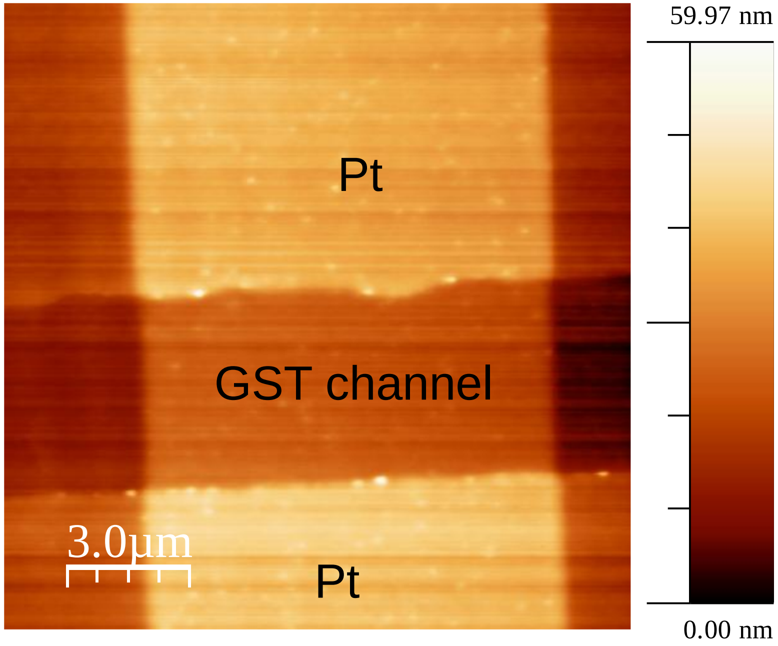
Thermal map

carbon fiber – epoxy composite *(*Anasys Instruments)*

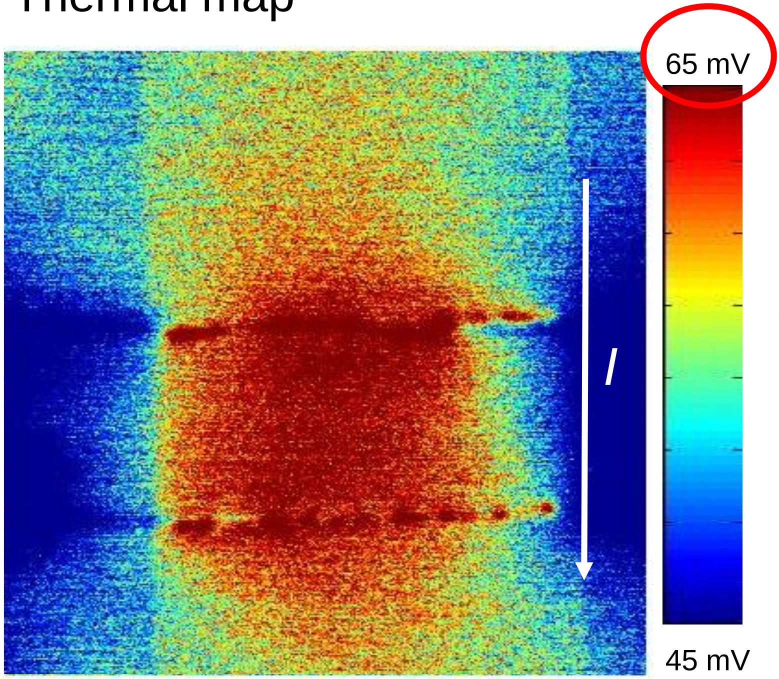
Thermal mapping of self-heating GST device

- $Ge_2Sb_2Te_5$ (GST) device

Topography



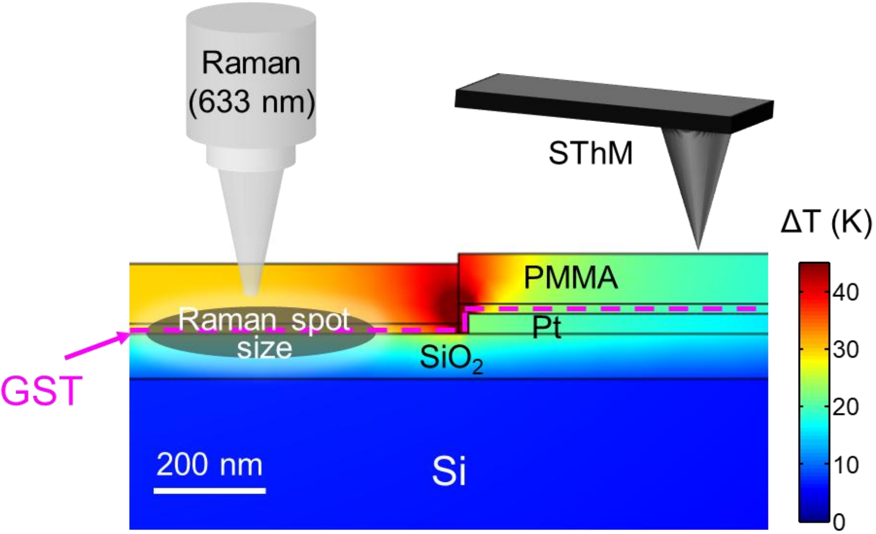
Thermal map



V=7V
I= 261 µA

E. Yalon, S Deshmukh, M. Muñoz-Rojo […], E Pop, *Scientific Reports*, 7, (1) 2018

Sensing mode: Temperature calibrated with Raman

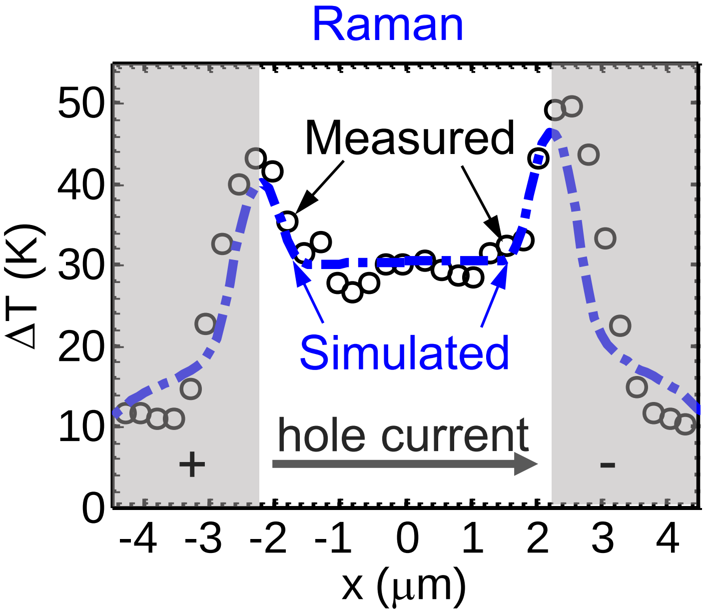


Thermal properties (simulation):

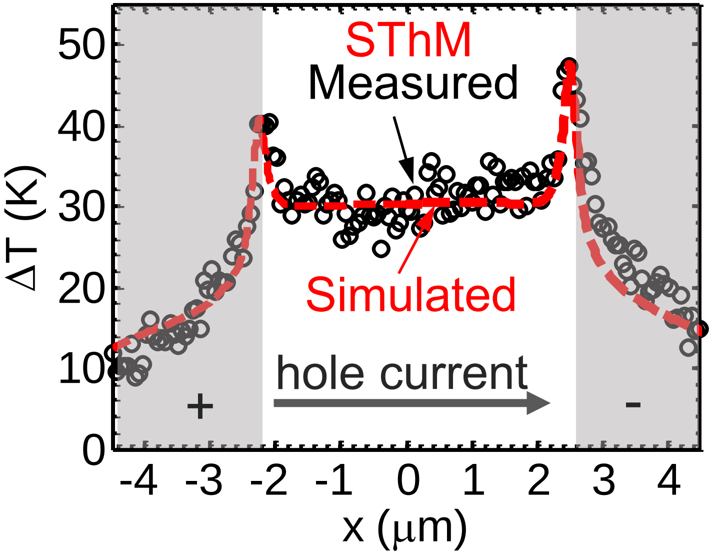
$\text{TBC}_{\text{GST/SiO2}}$ = 50 MW/m^2/K

$\text{TBC}_{\text{GST/Pt}}$ = 100 MW/m^2/K

GST thermopower = 450 µV/K (lumped thermoelectric with thermionic effect)

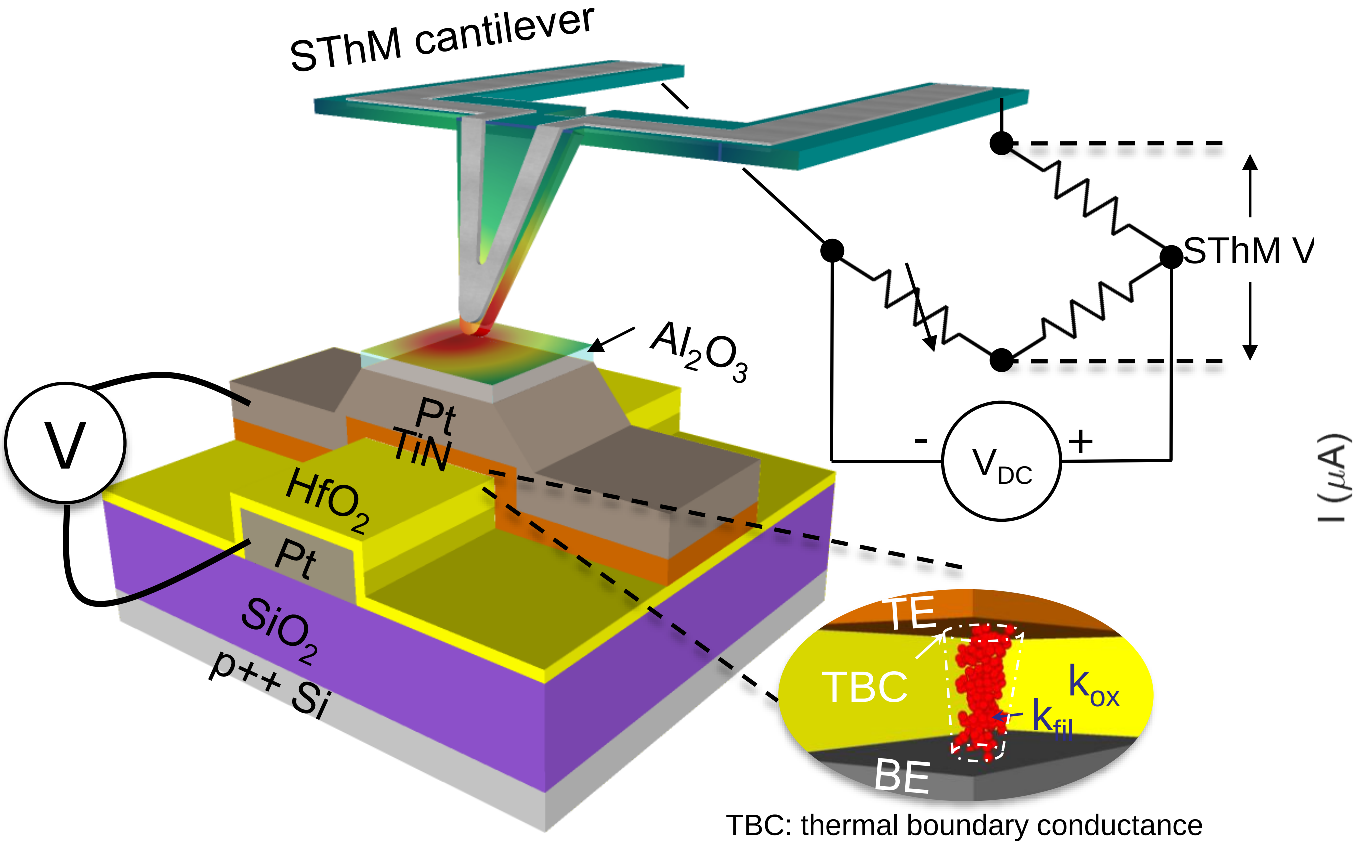


Significant heating at contacts

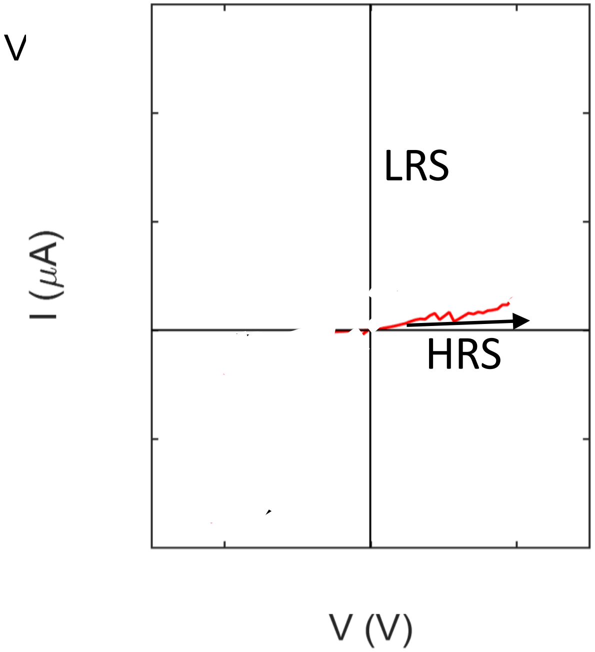


E. Yalon, S Deshmukh, M. Muñoz-Rojo […], E Pop, *Scientific Reports*, 7, (1) 2018

SThM on RRAM Devices



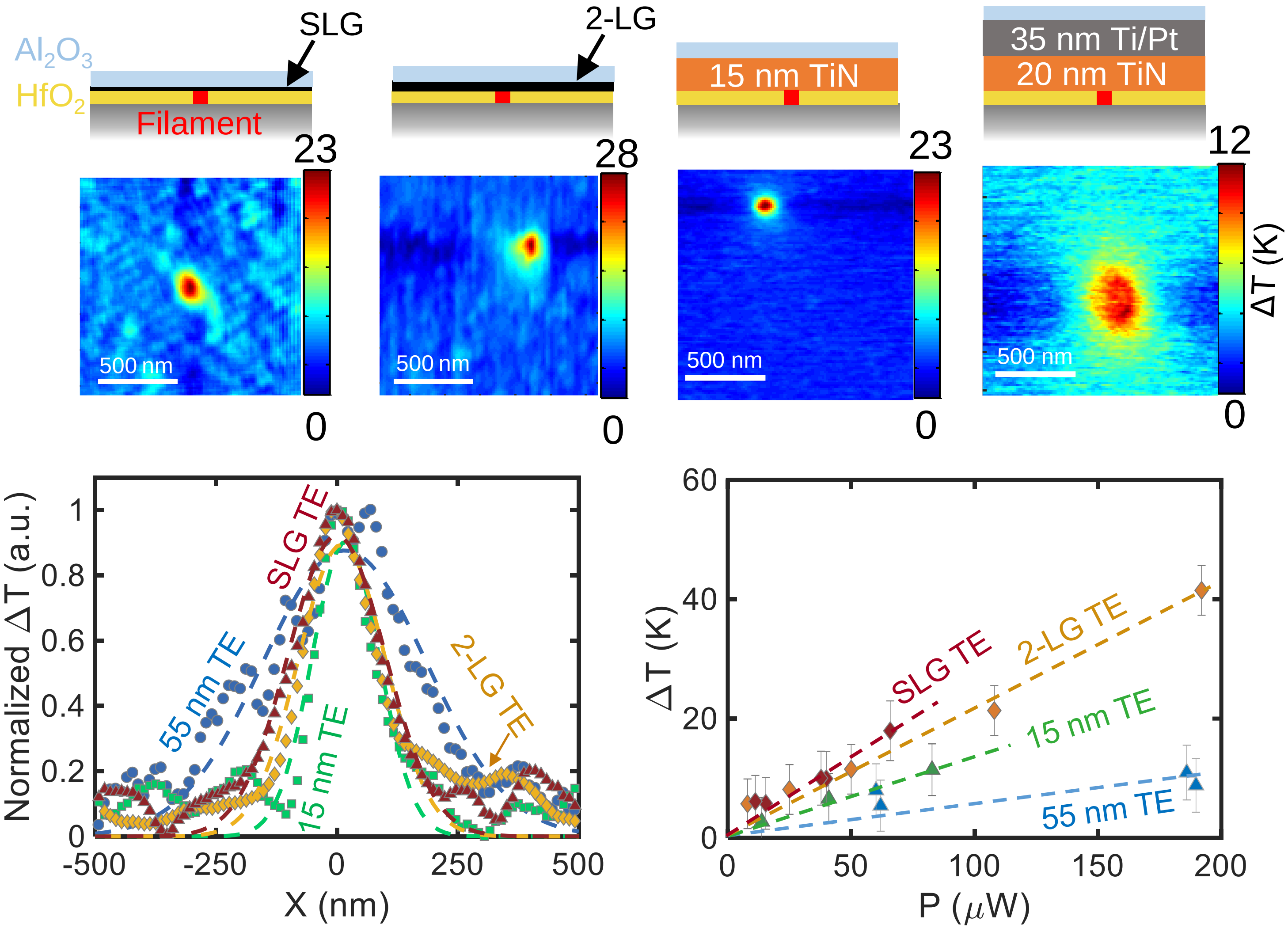
TBC: thermal boundary conductance



- HfO$_2$ RRAM devices with filaments self-heat because of external bias (**V**)

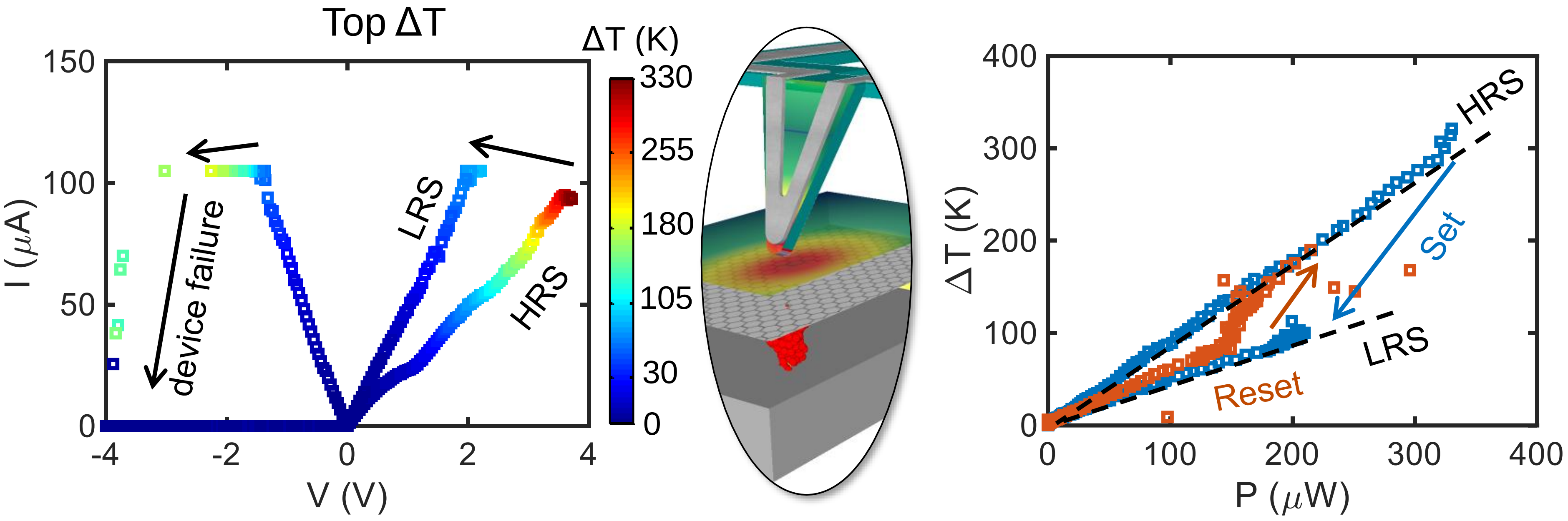
S. Deshmukh*, **M. Muñoz Rojo *,** …, E. Pop, *Science Adv., 2022*

Comparing Hot Spots Across Devices



- Top temperatures are comparable across different TE thickness

In operando SThM – Graphene as TE

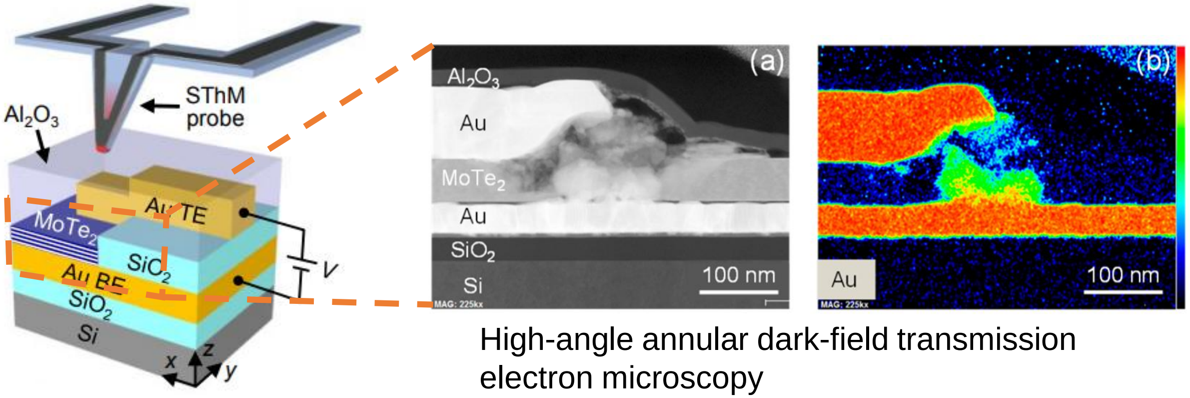


- Switching **ΔT_{fil}> ΔT_{top}> 300 K** above room temperature (RT).
- Dependence of top ΔT on power changes reversibly with switching
- Device failure (eventual hard reset) at relatively low ΔT.

S. Deshmukh*, **M. Muñoz Rojo *,** …, E. Pop, *Science Adv., 2022*

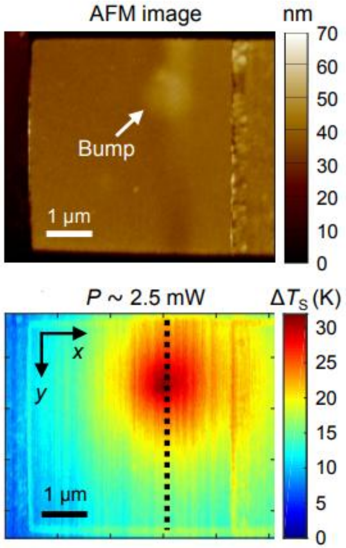
Thermal mapping extended to other devices

- CB-RAMs based on 2D materials

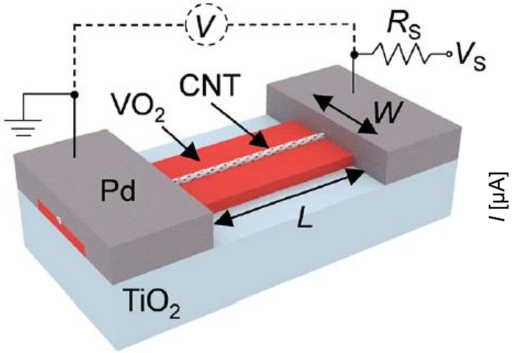


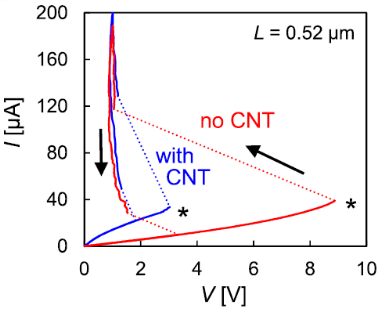
High-angle annular dark-field transmission electron microscopy

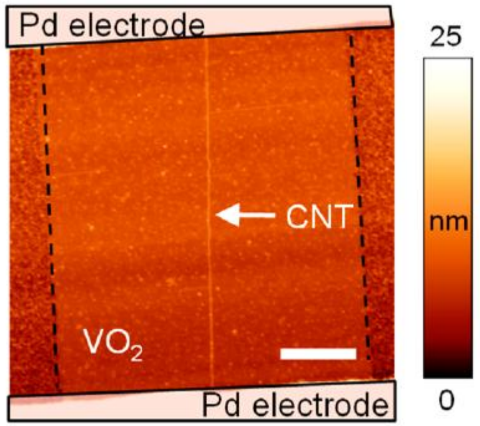
I. Datye, M. Muñoz Rojo, […], E. Pop, *Nano Letters*, 2020

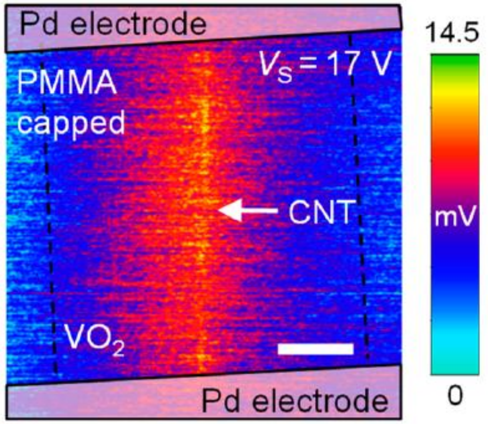


- VO_2 phase change triggered by CNTs







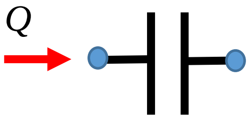


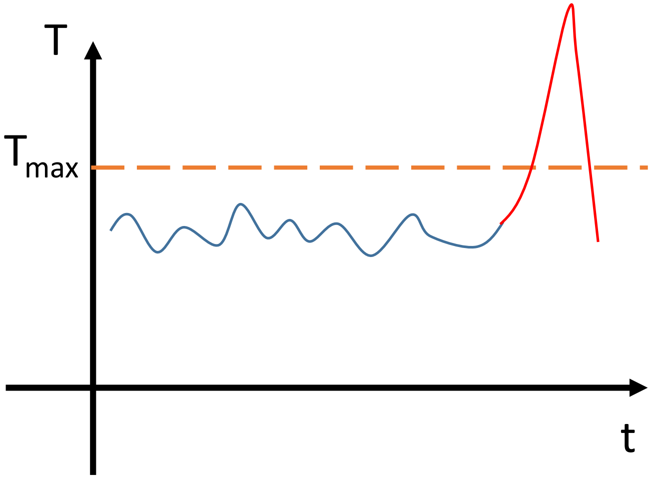
S. Bohaichuck, M. Muñoz Rojo, […], E. Pop, *Nano Letters*, 2020

Solid-state thermal management

Thermal mismanagement of electronics and beyond….

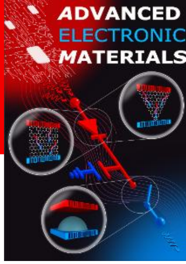
Nowadays limited by
thermal resistors & capacitors





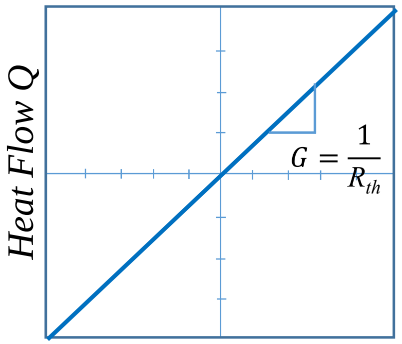
Thermal devices

Swoboda et al., Solid-state thermal control devices, Adv. Elect. Mat., 2021



Passive thermal device

**Transfer Function:
Symmetric**



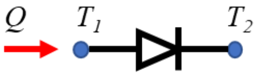
Thermal Bias: $\Delta T = T_1 - T_2$
(T_{avg} fixed)

$$\Delta T = Q \times R_{th}$$

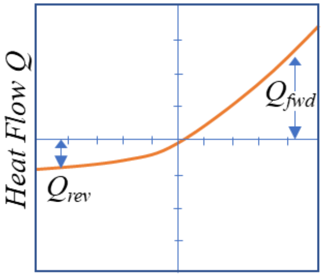
$$R_{th} = \frac{1}{k} \cdot \frac{L}{A}$$

Active thermal devices

a) Diode

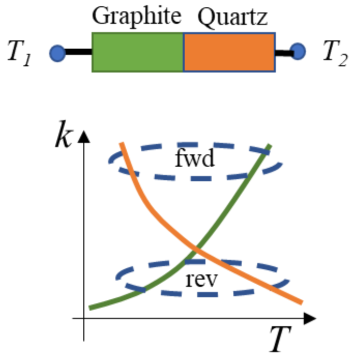


**Transfer Function:
Asymmetric**



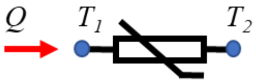
Thermal Bias: $\Delta T = T_1 - T_2$
(T_{avg} fixed)

Example

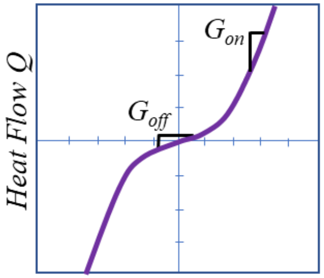


C. Dames, *J. Heat Transfer*, **131**, 061301 (2009)

b) Regulator

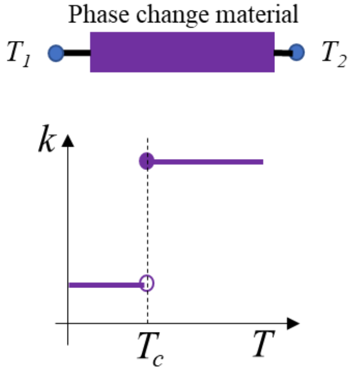


**Transfer Function:
Nonlinear**



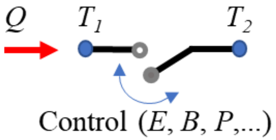
Thermal Bias: $\Delta T = T_1 - T_2$
(T_{avg} fixed)

Example

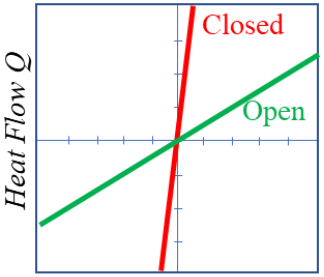


Xie *et al.*, *Adv. Funct. Mater.*, **21**, 1602 (2011)

c) Switch

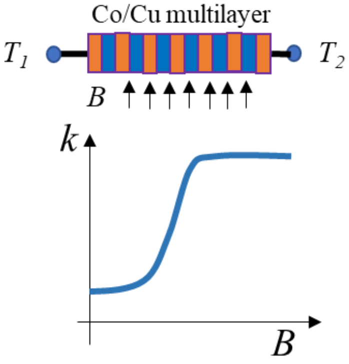


**Transfer Function:
Control dependent**



Thermal Bias: $\Delta T = T_1 - T_2$
(T_{avg} fixed)

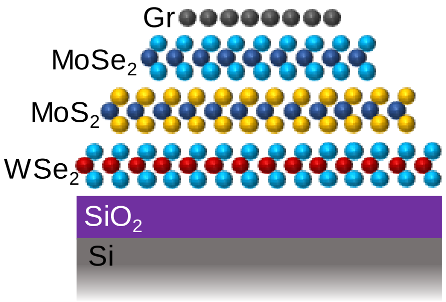
Example

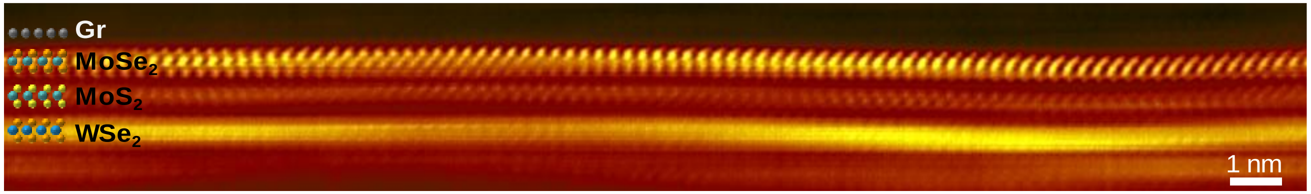


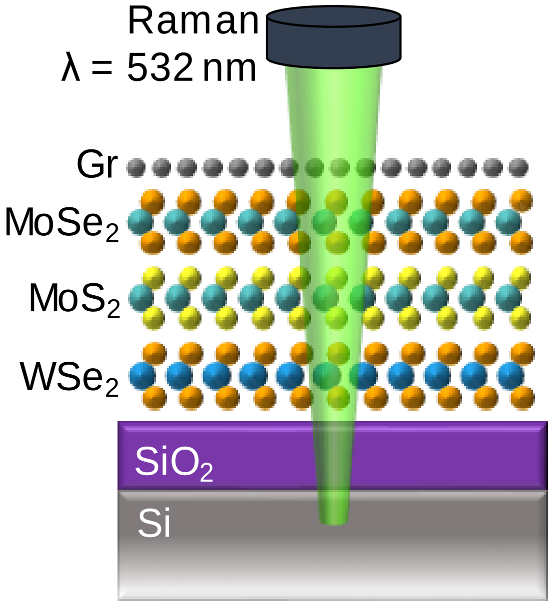
Kimling *et al.*, *Phys. Rev. B*, **91**, 144405 (2015)

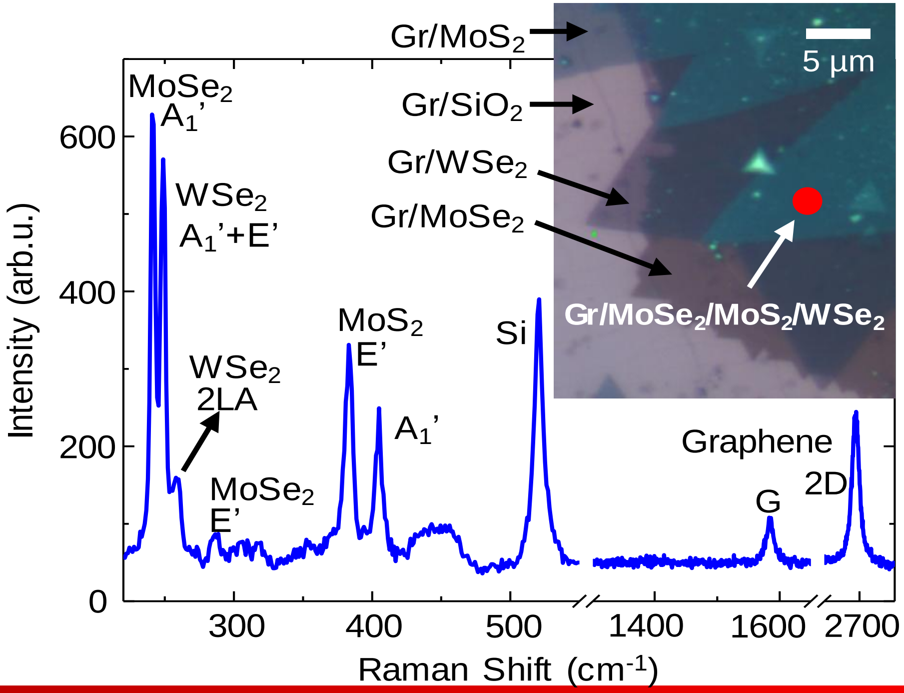
Ultra-thin thermal barriers

- Need for ultra-thin and high thermal resistive barriers
- Routing heat to desired locations

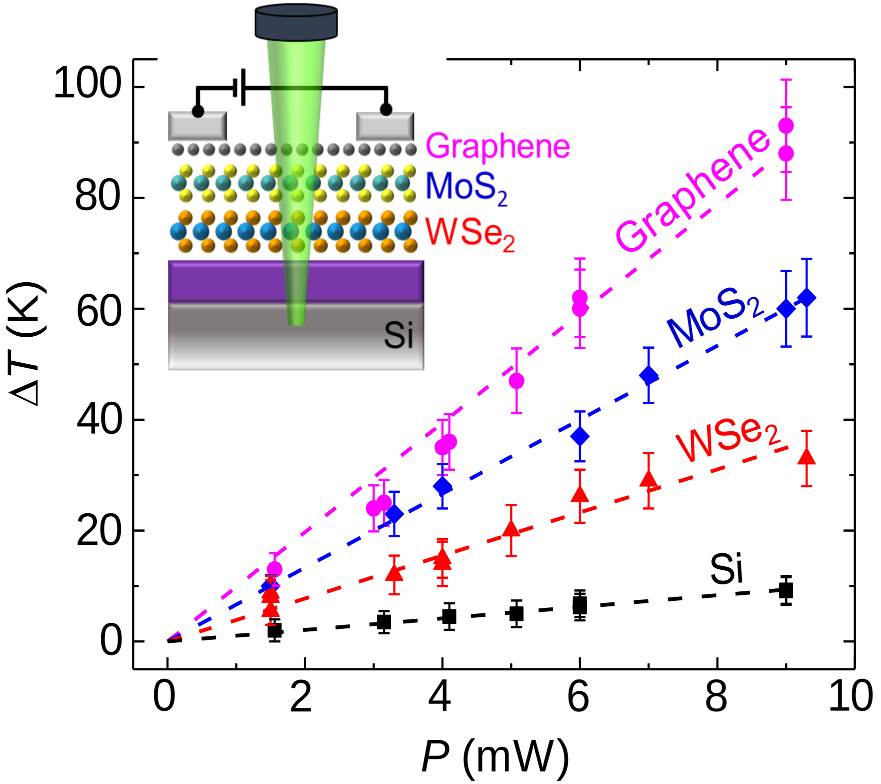


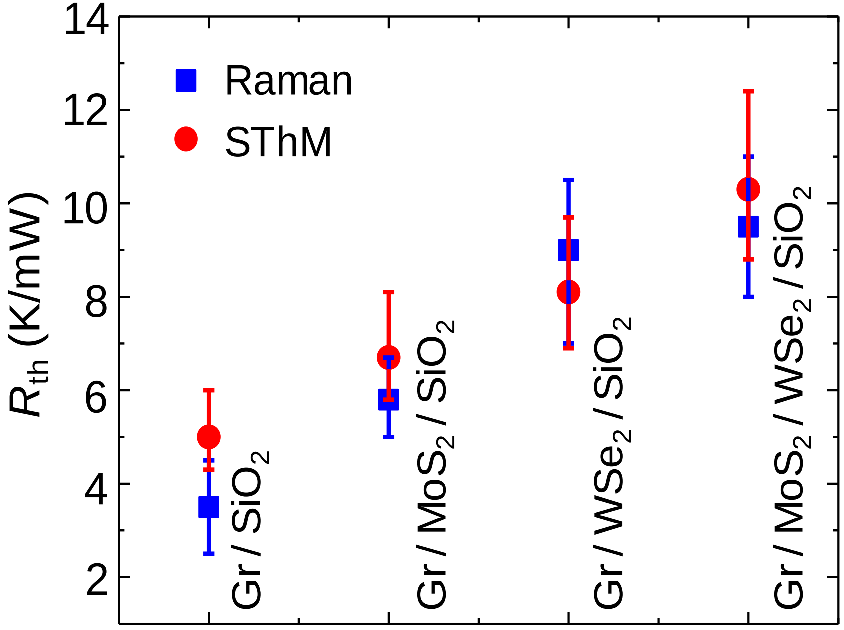






Thermal barriers based on 2D heterostructures





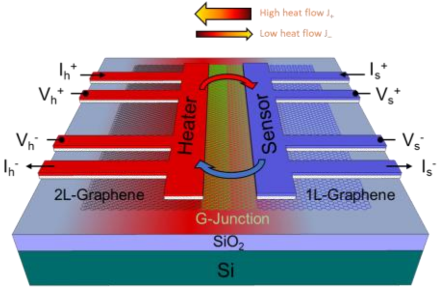
- Stack thickness ~3 nm with clean, residue free interfaces
- Artificial stack (Gr-MoS$_2$-WSe$_2$) possess a thermal resistance equivalent to 300nm SiO$_2$
- Thermal barriers for thermal routing applications

S. Vaziri*, E. Yalon*, **M. Muñoz Rojo** *et al*, *Science Advances,* 2019

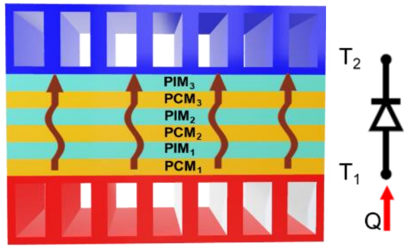
Non Linear Thermal Control Devices

Thermal diodes

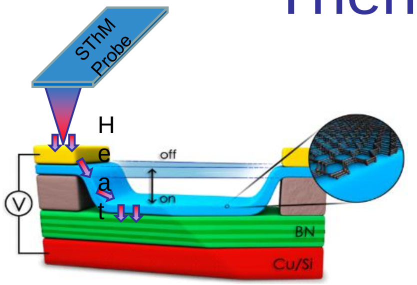
Thermal switches



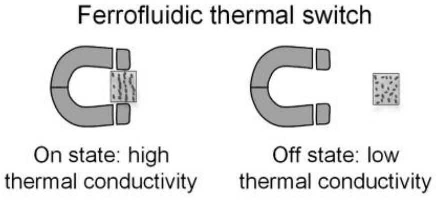
M. Muñoz Rojo *et al*, *2D Materials*, 6, (1) 2018



T. Swoboda, K. Klinar, S. Abbasi, G. Brem, A. Kitanvosky, & M. Muñoz Rojo, *iScience*, **24**, (2021)

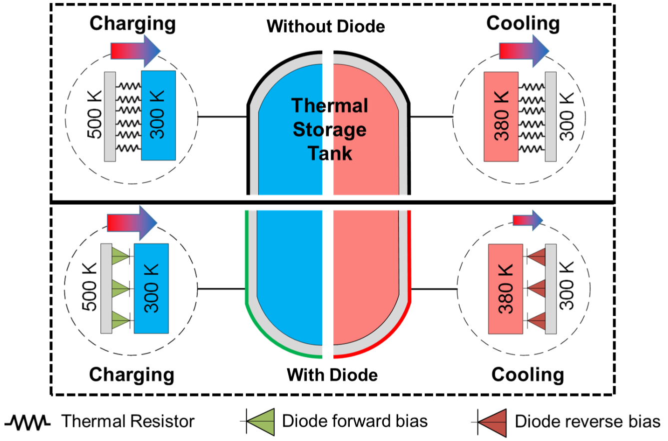


M. Chen, M. Muñoz Rojo, F. Lian and E. Pop. *2D materials, 8, (3)* (2022)

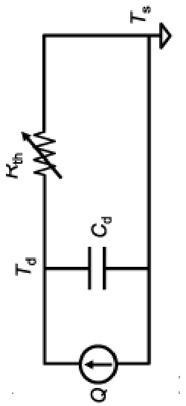


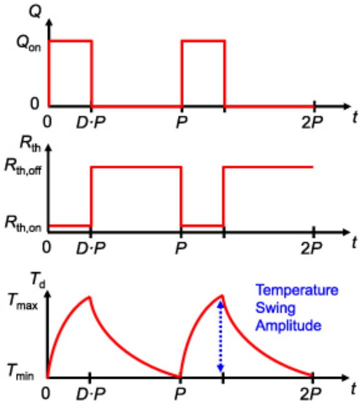
K. Klinar, T. Swoboda, M. Muñoz Rojo and A. Kitanovski, iScience 25, (2022)

Applied to heat batteries, thermal management of electronics or magnetocaloric refrigeration:



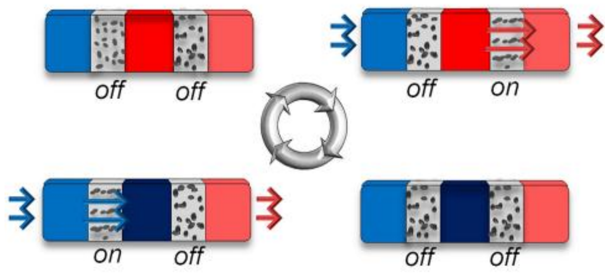
T. Swoboda, K. Klinar, S. Abbasi, G. Brem, A. Kitanvosky, & M. Muñoz Rojo, *iScience*, **24**, (2021)





M. Chen, M. Muñoz Rojo, F. Lian and E. Pop. *2D materials, 8, (3)* (2022)

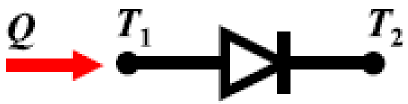
Ferrofluidic thermal switches in a magnetocaloric device



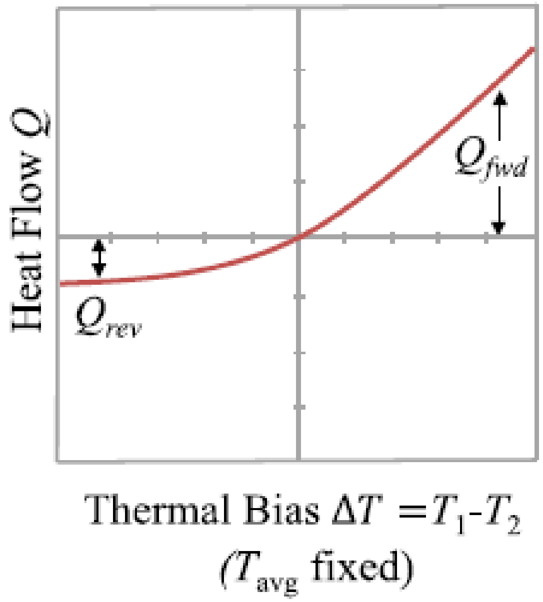
K. Klinar, T. Swoboda, M. Muñoz Rojo and A. Kitanovski, iScience 25, (2022)

Thermal Rectification

Diode



Transfer Function: Asymmetric

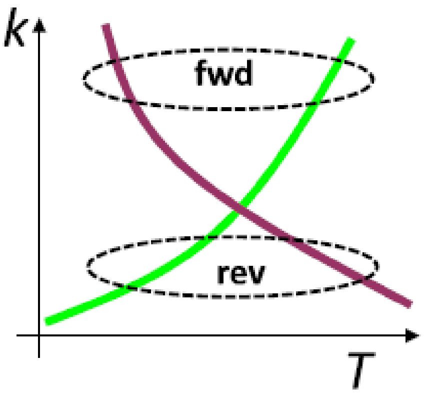


$$RR = \frac{Q_{fwd} - Q_{rev}}{Q_{rev}}$$

G. Wehmeyer *et al. Appl. Phys. Rev.* **4**, 041304 (2017)

Examples

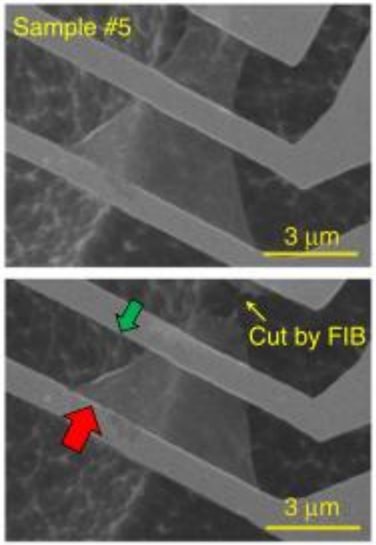
Junction of Materials with Different Thermal Properties (JMT)



$RR \sim 70\ \%$

Low temperatures

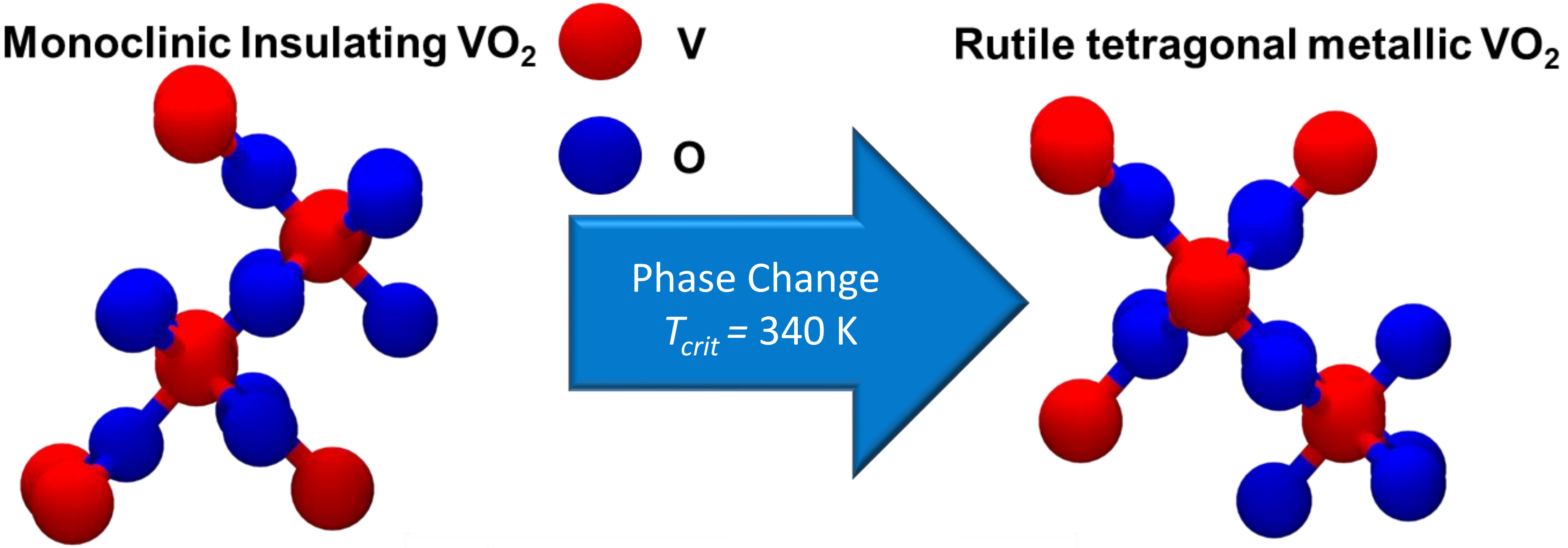
Shape-Induced Thermal Diodes (SID)



$RR \sim 11\ \%$

Low RR

Phase change materials



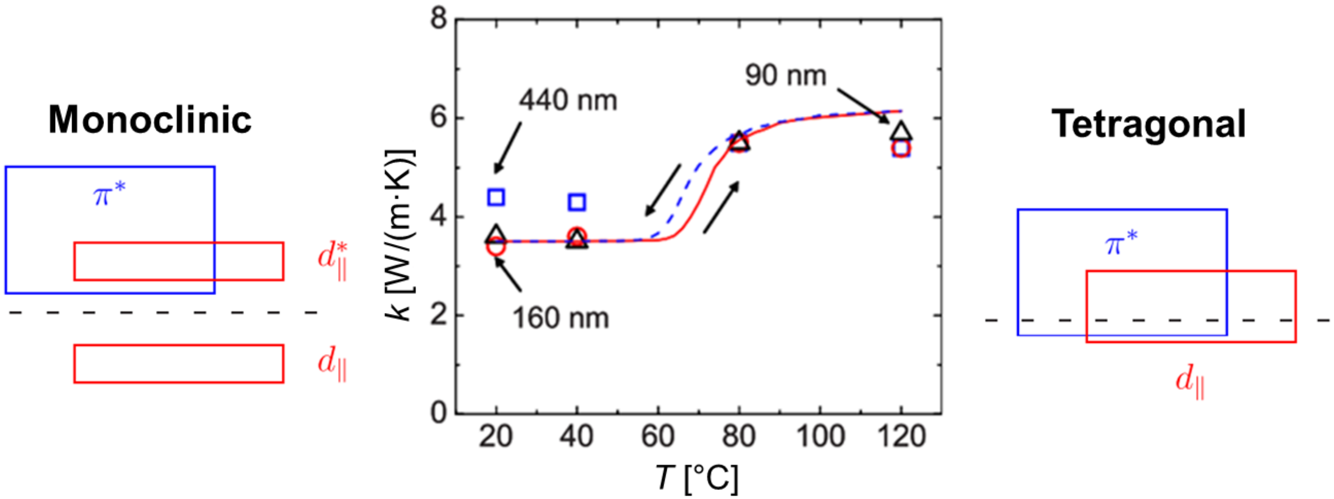
Monoclinic Insulating VO_2

V

O

Phase Change
T_{crit} = 340 K

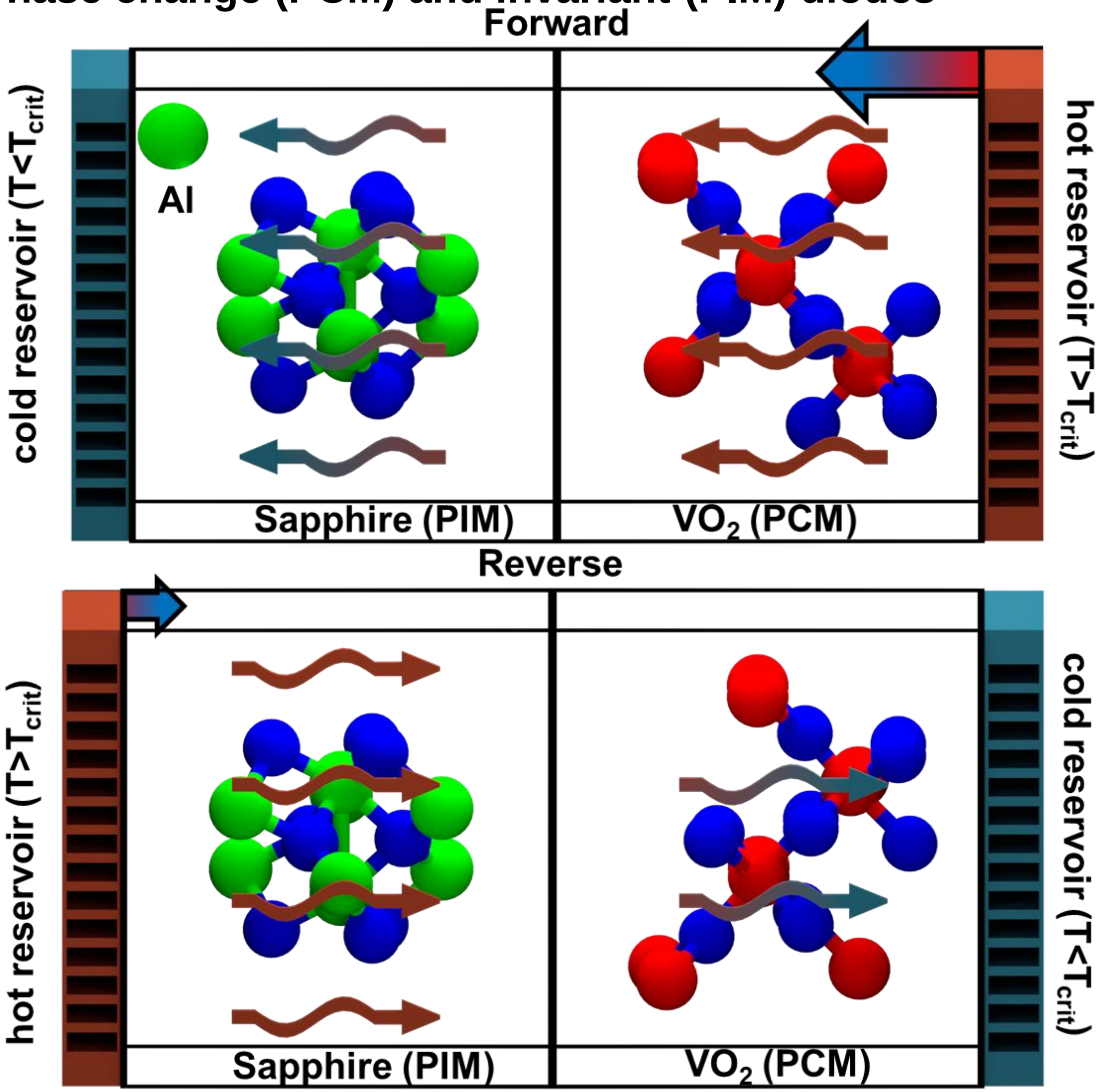
Rutile tetragonal metallic VO_2



Swoboda *et al. Adv. Electron. Mater.* **7**, 2000624 (2020)

PCM thermal diodes

Phase change (PCM) and invariant (PIM) diodes



Swoboda *et al. Adv. Electron. Mater.* **7**, 2000624 (2020)

$T\,(VO_2) > T_{crit}\,(VO_2)$

$k\,(VO_2) \rightarrow$ **high**

$T\,(VO_2) < T_{crit}\,(VO_2)$

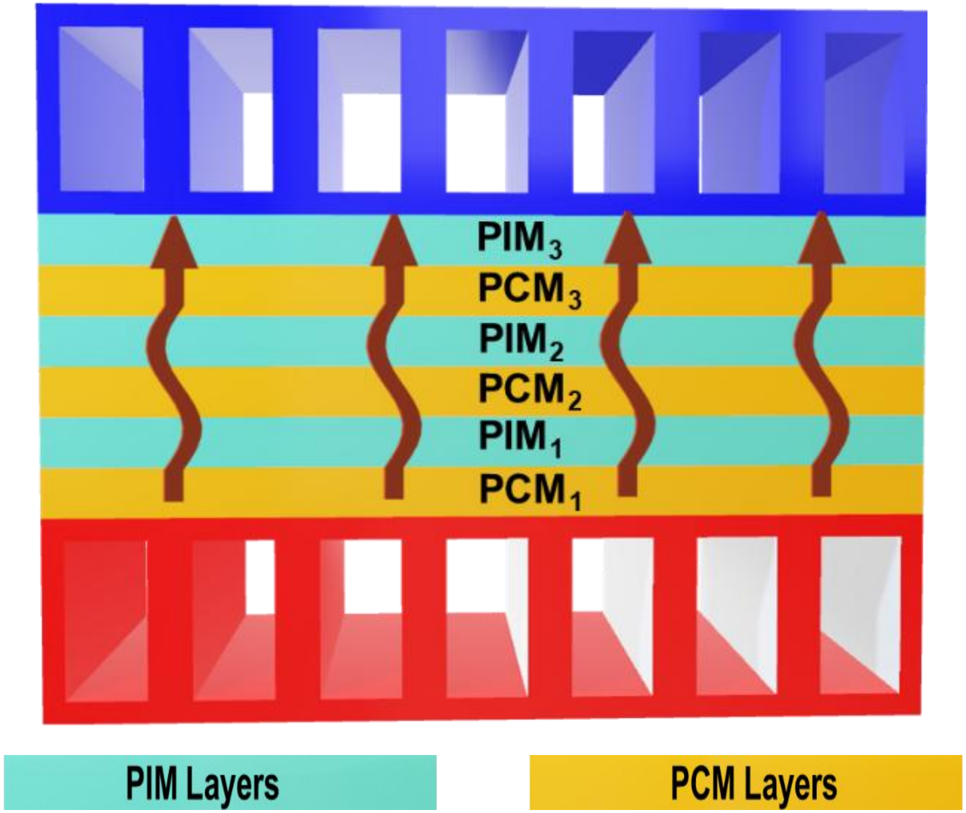
$k\,(VO_2) \rightarrow$ **low**

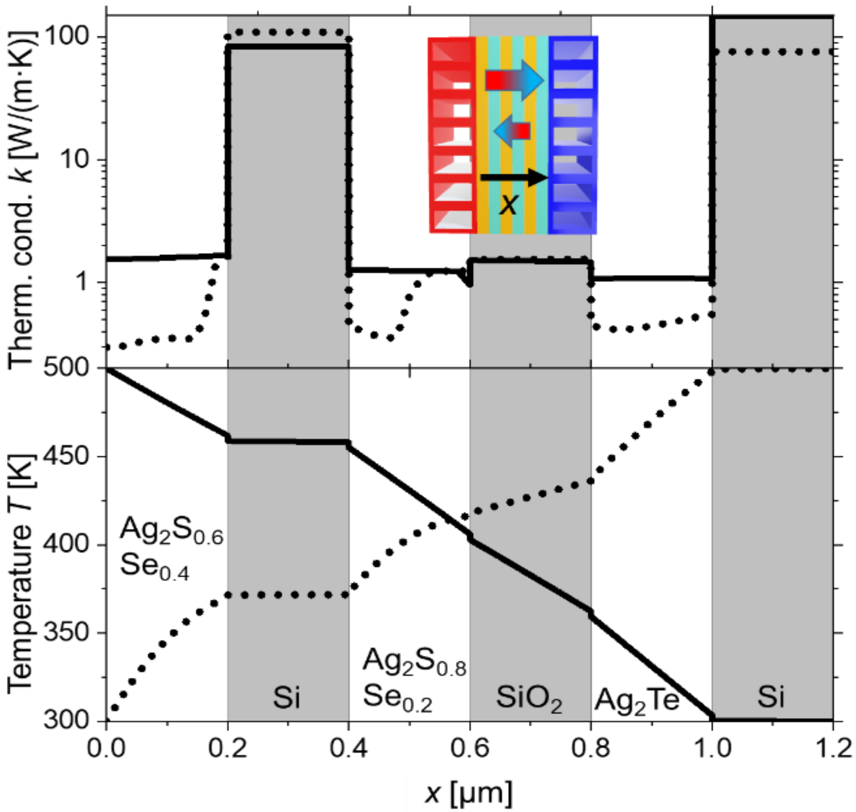
$$Q_{fwd} > Q_{rev}$$

Multiple PCM/PIM diode design

- T_{source} = 500 K; T_{sink} = 300 K

Finite Element Modelling (FEM)





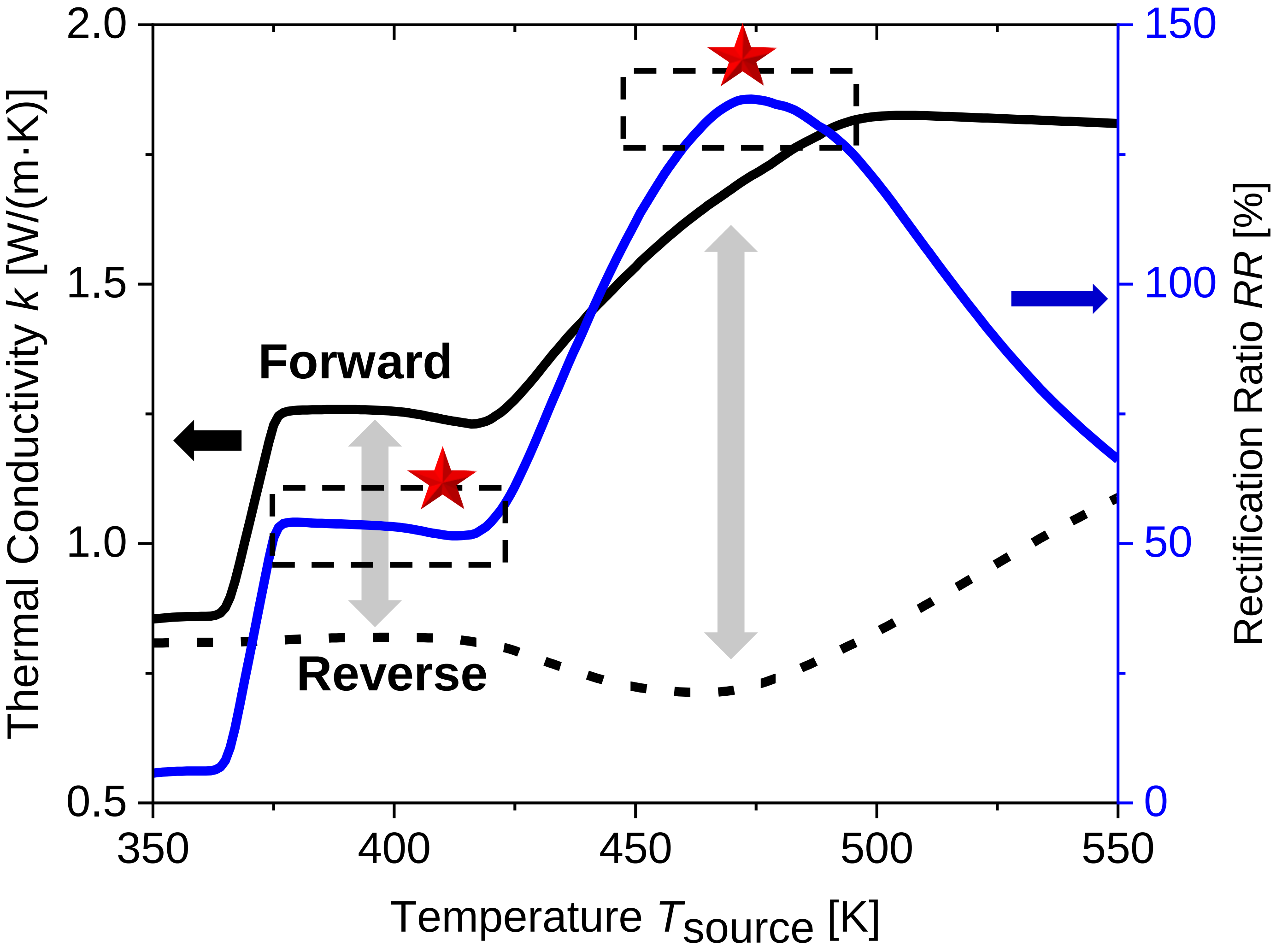
Solid Line: Forward; Dotted Line: Reverse

Max *RR* = 119 %

$$RR = \frac{Q_{fwd} - Q_{rev}}{Q_{rev}}$$

Swoboda *et al.* *iScience*, **24**, 102843 (2021)

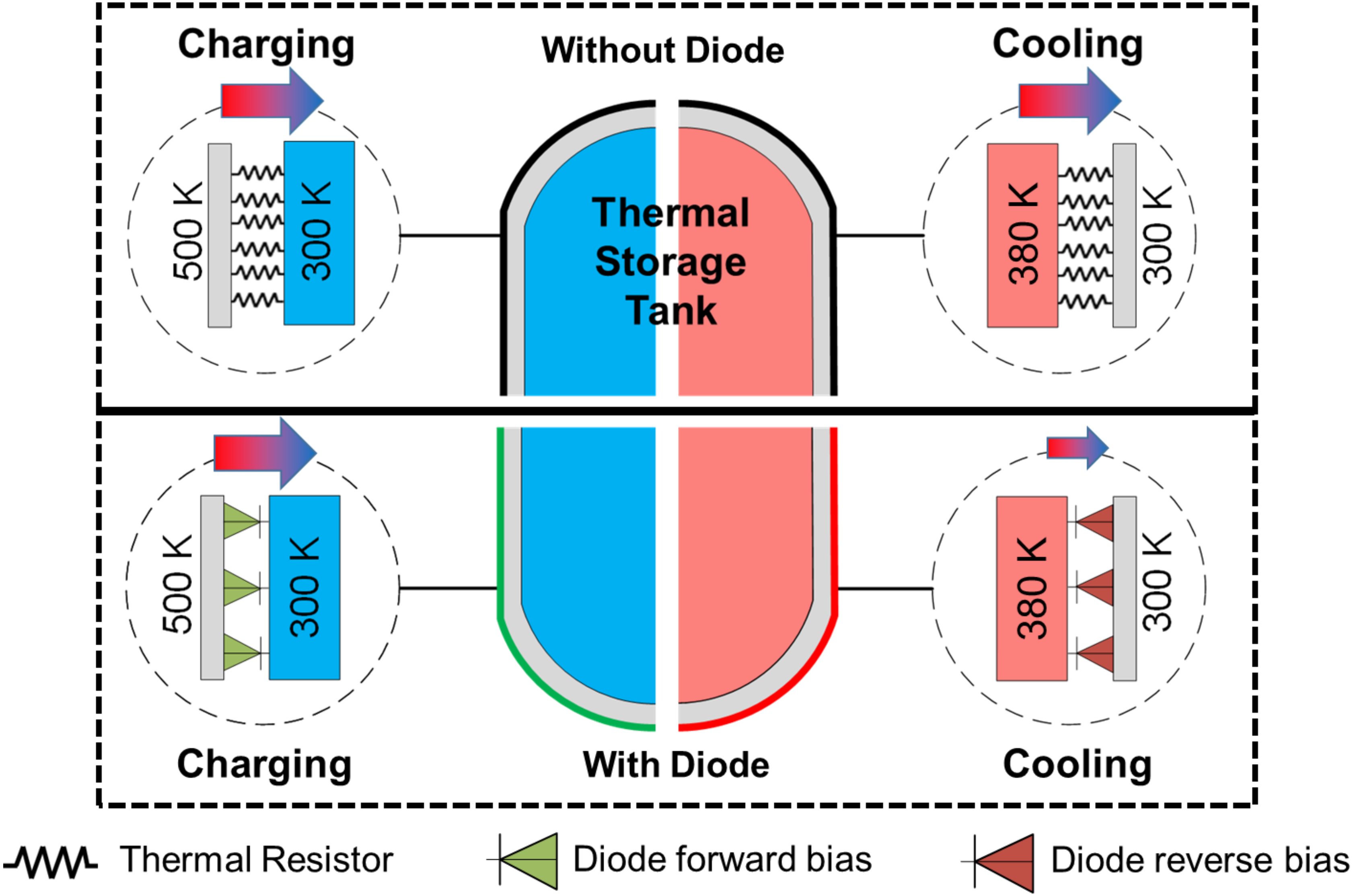
3 PCM Thermal Rectification vs Temperature



- High Rectification Ratio – max 136 %
- Temperature modulation

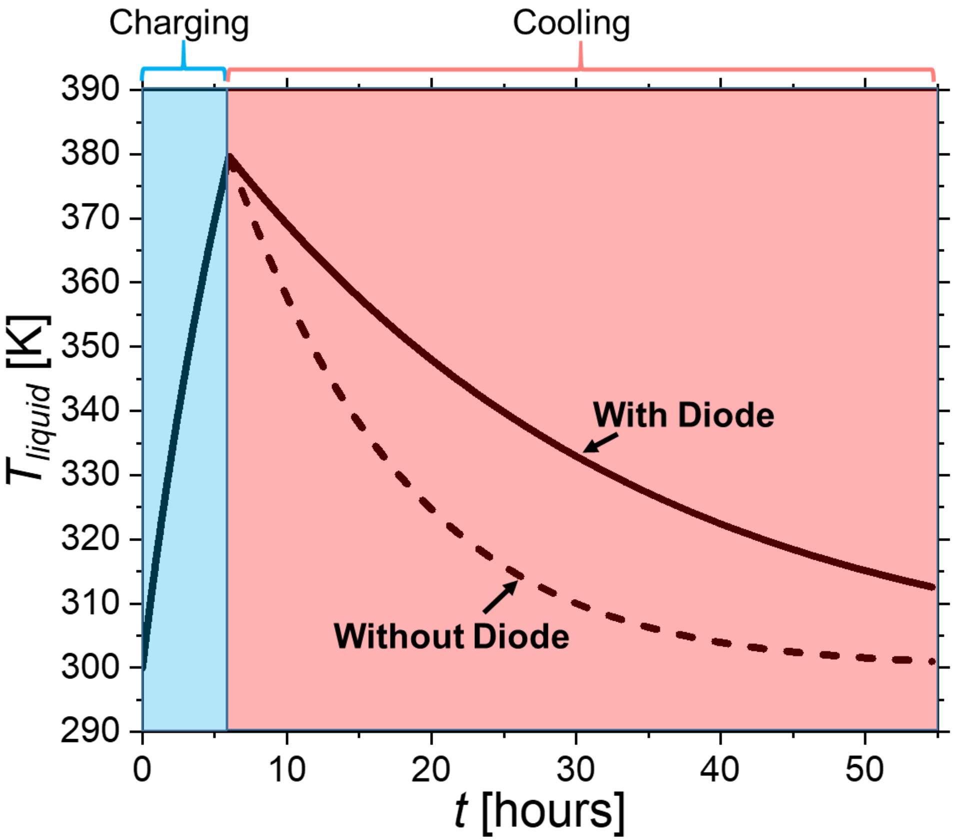
$$RR = \frac{Q_{fwd} - Q_{rev}}{Q_{rev}}$$

Thermal diodes for energy storage

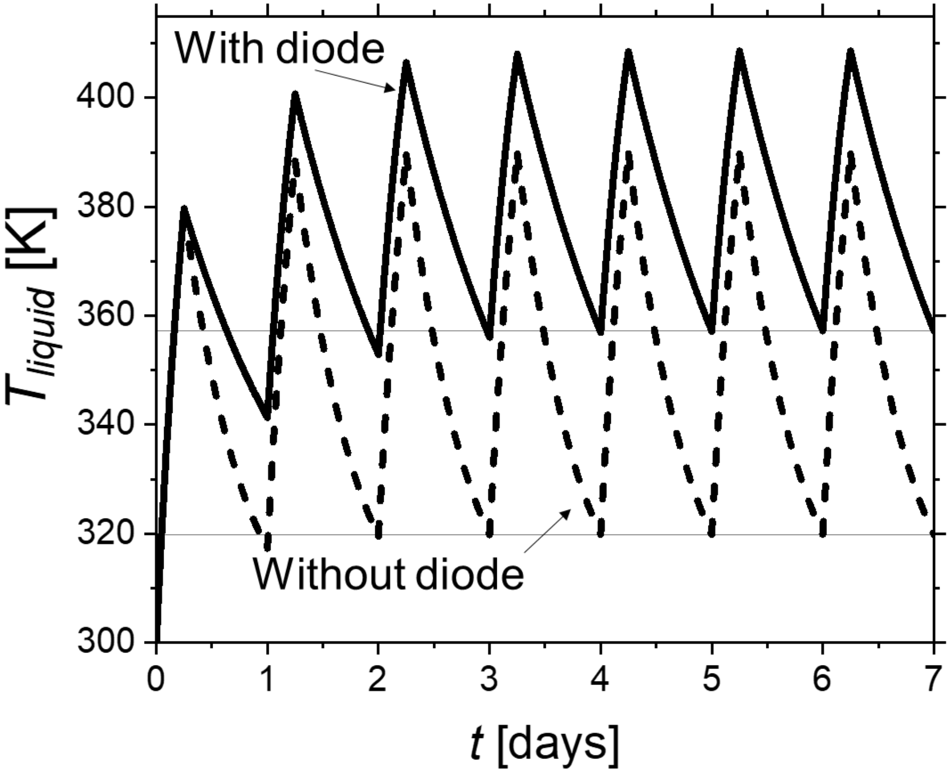


Swoboda *et al.* *iScience*, **24**, 102843 (2021)

Heat Retention



Cooling to original state

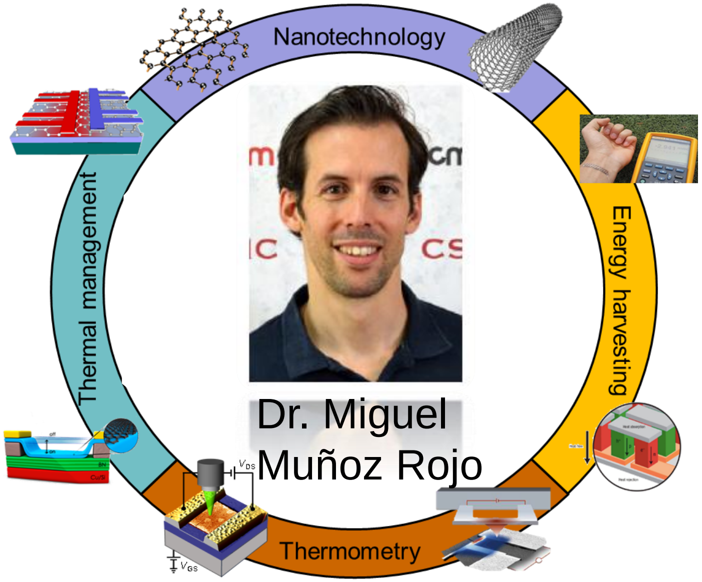


7 – Day cycle

- Diode configuration is able to retain more energy

Swoboda *et al. iScience*, **24**, 102843 (2021)

Thank you for your attention!



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Selected publications:

- M. Muñoz Rojo, et al., **Science Advances**, 8, 13, 2022
- K. Zhu, [..], M. Muñoz Rojo, et al., **Nature**, 618, 57-62, 2023
- I. Datye, M. Muñoz Rojo, et al., **Nano Letters**, 20, 2, 2020
- M. Muñoz Rojo, **Adv. Funct. Mat.,** 30, 18, 2020
- S. Bohaichuk, M. Muñoz Rojo, **ACS Nano**, 13, 10, 2019
- E. Yalon, S. Deshmukh, M. Muñoz Rojo,et al. **Sci.Rep.**, 2017