TFAWS Passive Thermal Paper Session

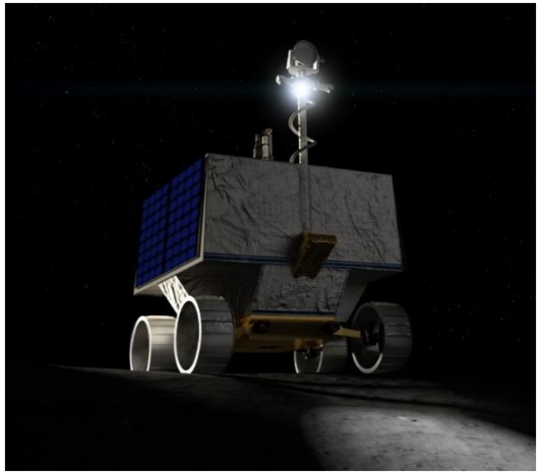
Passive thermal control of spacecraft utilizing temperature dependent magnetic forces

Lorenzo Castelli, Ajay Garg, Qing Zhu, Trevor Shimokusu, Pooja Sashital, Geoff Wehmeyer

Presented By
Lorenzo Castelli
Rice University

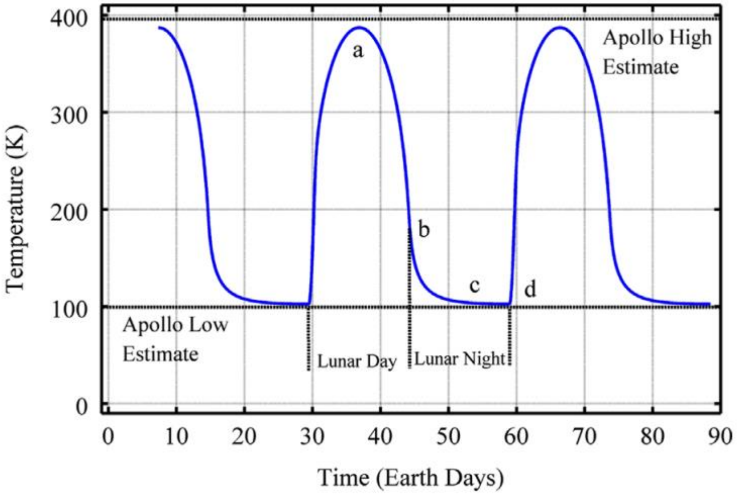
Thermal & Fluids Analysis Workshop
TFAWS 2023
August 21-25, 2023
NASA Goddard Space Flight Center
Greenbelt, MD

Need for switchable thermal devices in spacecraft



VIPER Lunar Rover (NASA)

Lunar equator $T(t)$; cold lunar nights



Malla & Brown. *Acta Astro.* 107 (2015): 196-207.

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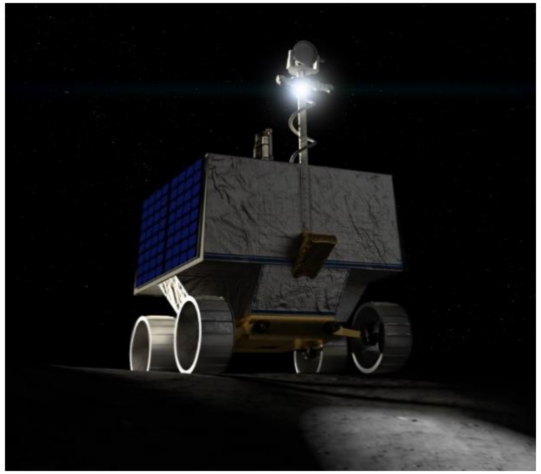

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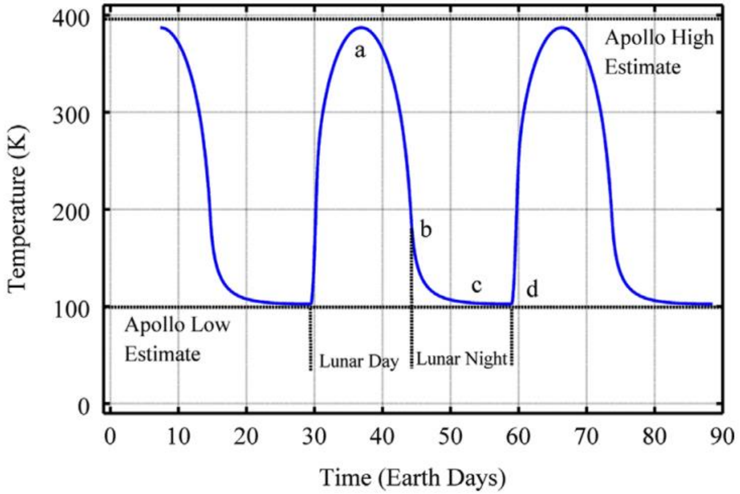

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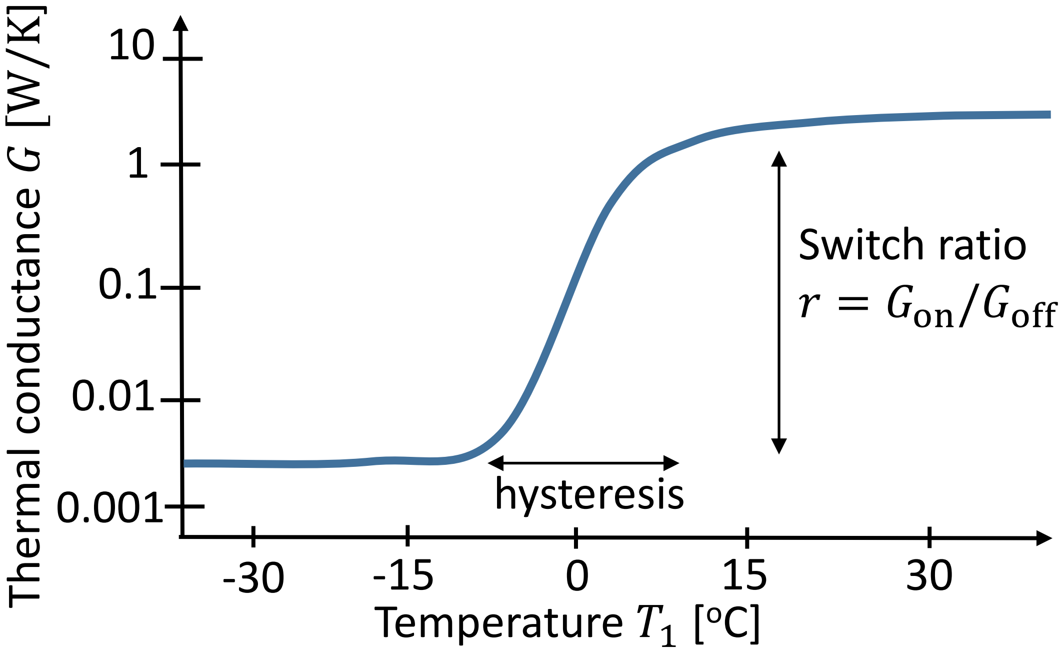
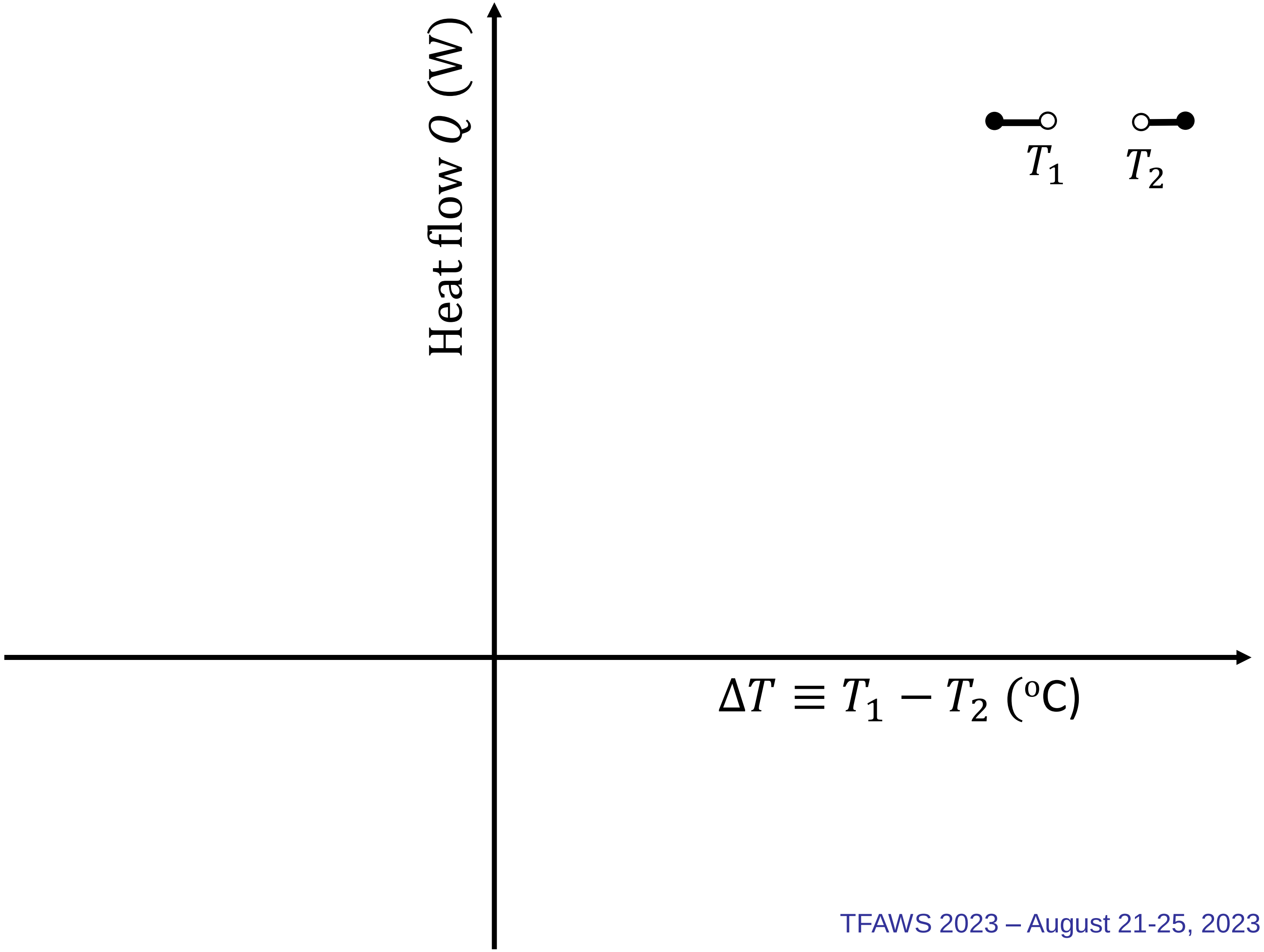
Thermal Challenges	Technology focus
Survive the long night with minimal energy available for heating and dissipate heat during day.	High switch ratio thermal device

Adapted from Chen, Sunada, Rodriguez, "JPL Advanced Thermal Control Technology Roadmap", Spacecraft Thermal Control Workshop, May 18 2021



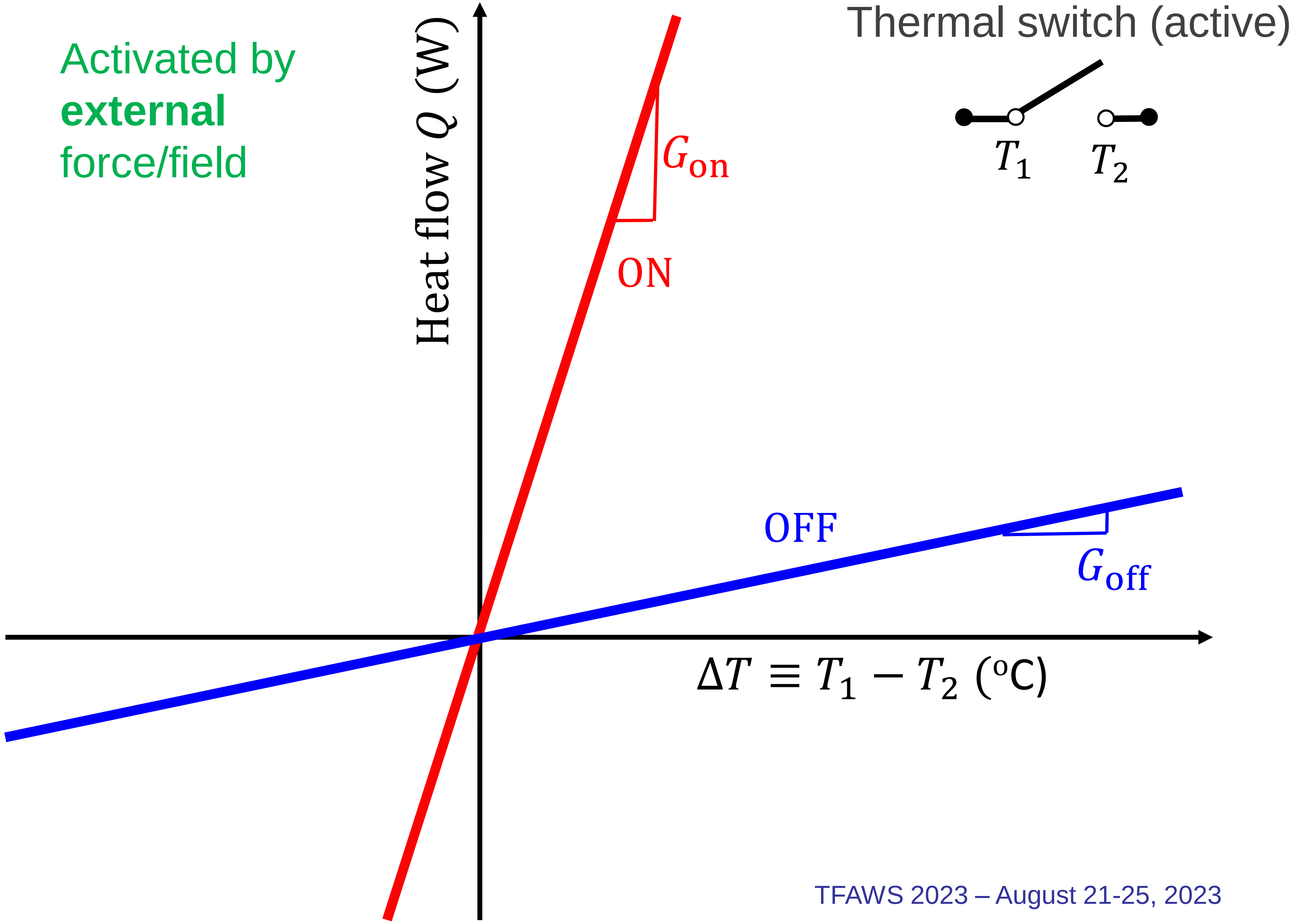
Goals
-Maximize switching ratio -Minimize thermal hysteresis -Thin devices <1cm -Minimize mass

A few option of variable insulation are available



A few option of variable insulation are available

Activated by **external** force/field



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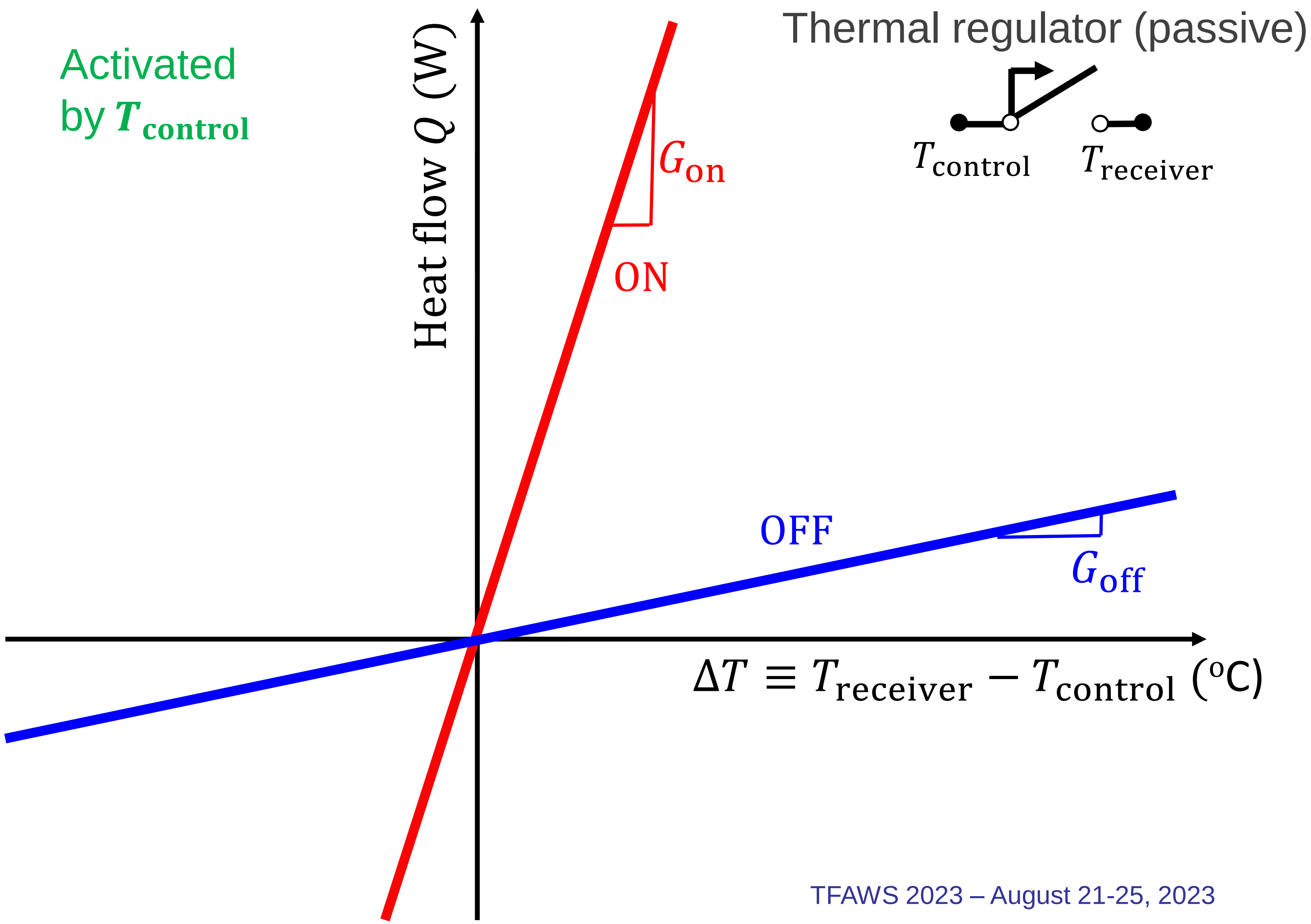
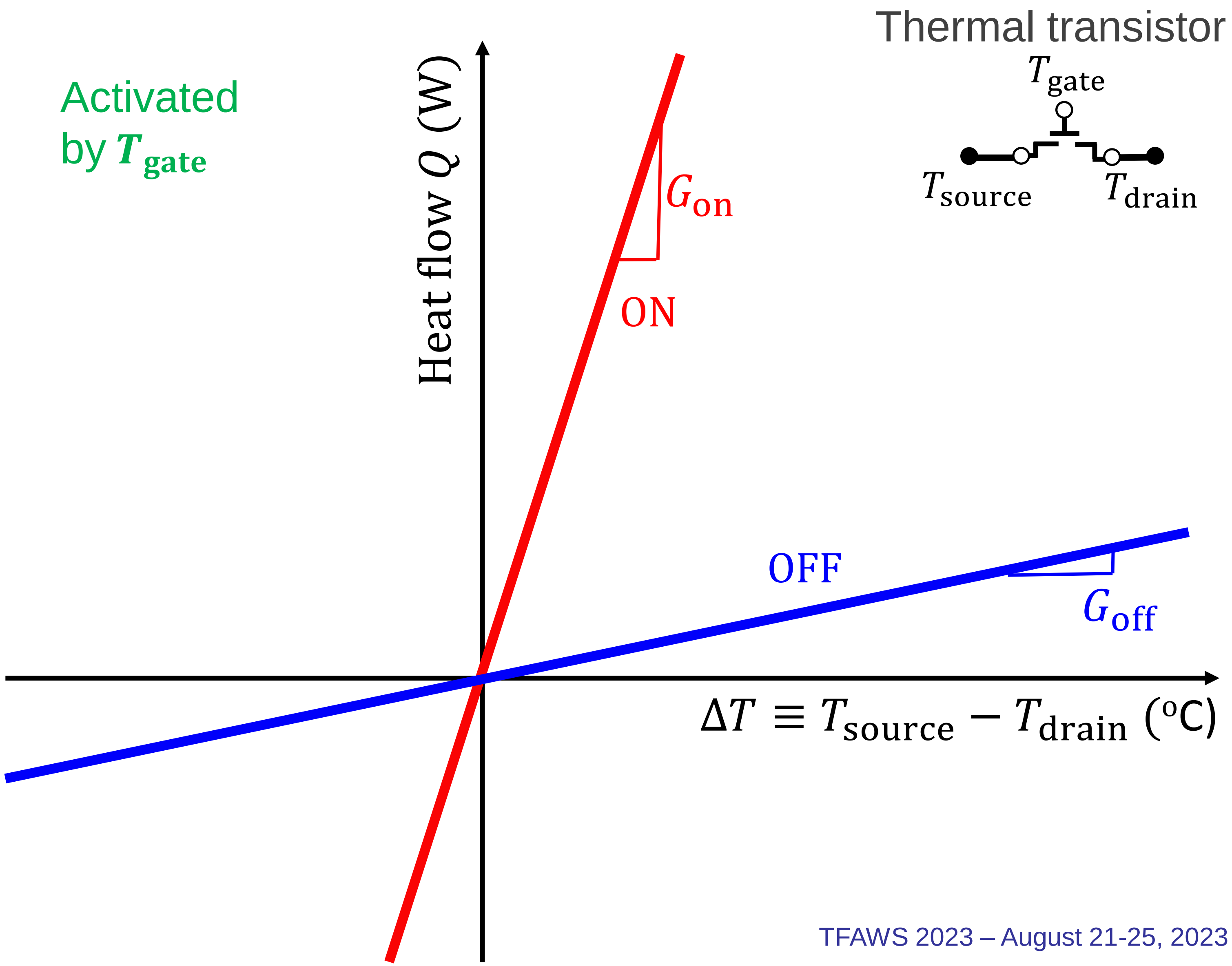


A few option of variable insulation are available

Activated by $\boldsymbol{T}_{\mathbf{gate}}$



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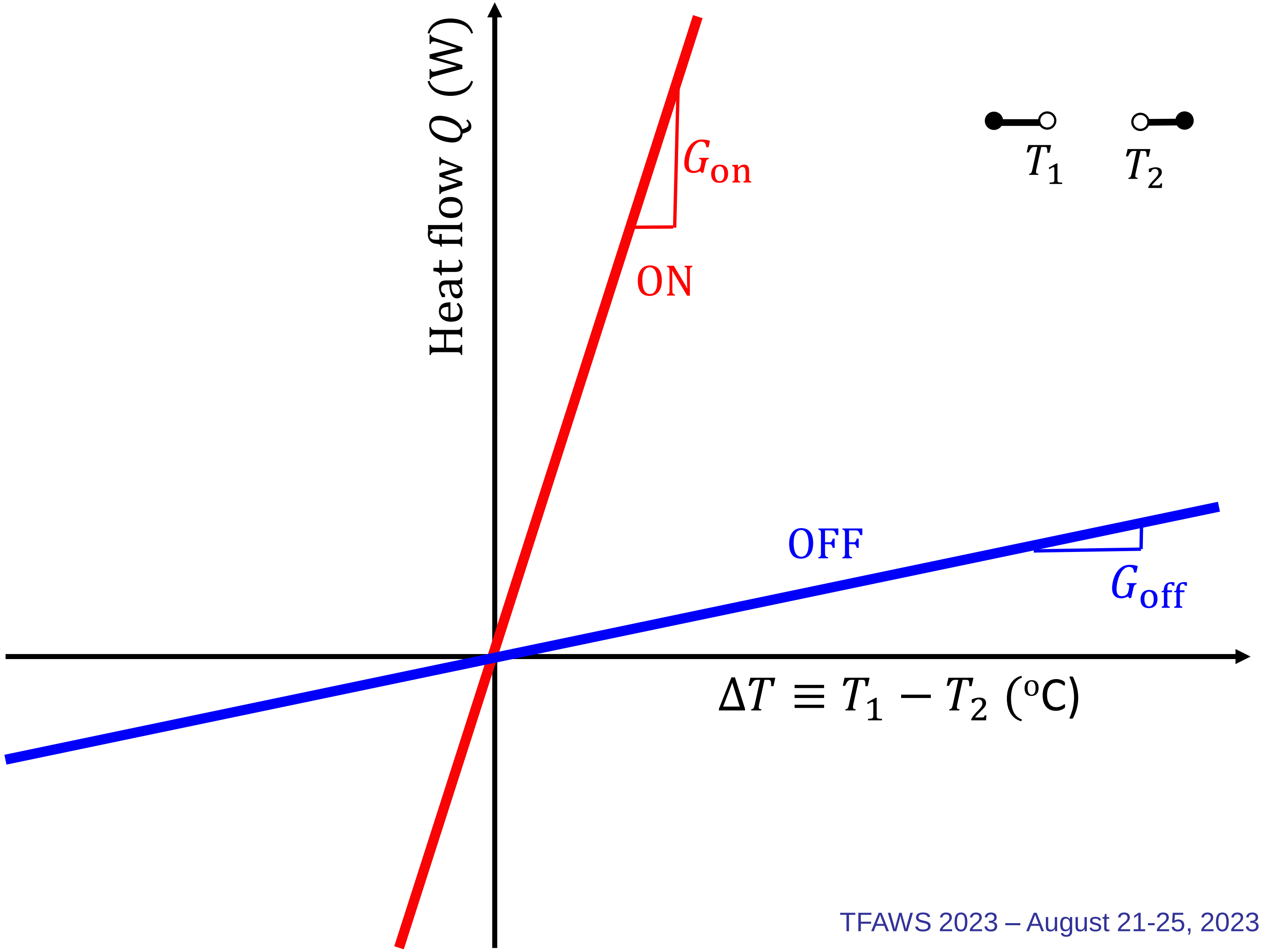
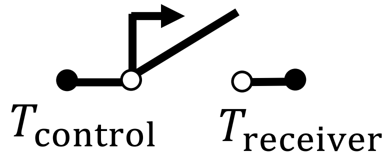


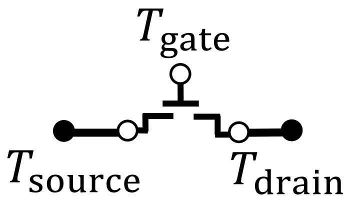
Focus of this presentation

Thermal regulator



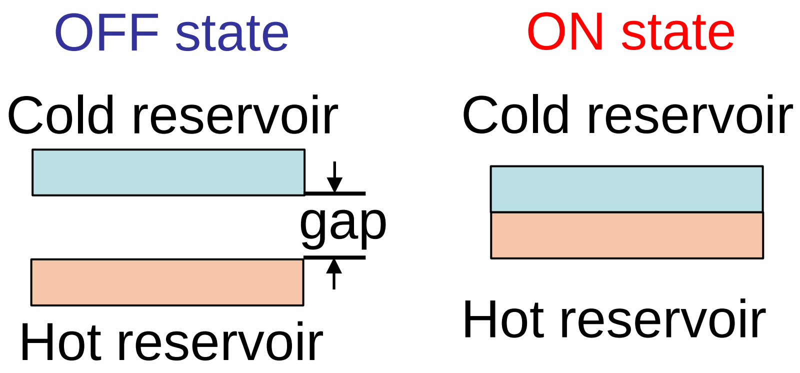
Castelli, L., Garg, A., Zhu, Q., Sashital, P., Shimokusu, T.J., and Wehmeyer, G. (2023). A thermal regulator using passive all-magnetic actuation. Cell Reports Physical Science, *Accepted*

Thermal transistor



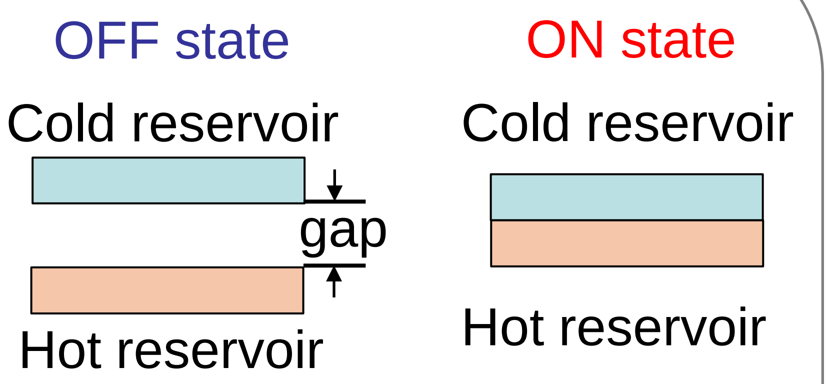
Castelli, L., Zhu, Q., Shimokusu, T.J., and Wehmeyer, G. (2023). A three-terminal magnetic thermal transistor. Nat Commun **14**

Contact based devices achieve highest performance



- OFF state
  - Parasitic conduction and radiation
- ON state
  - Conduction heat transfer through high thermal conductivity materials

Contact based devices achieve highest performance



- OFF state
  - Parasitic conduction and radiation
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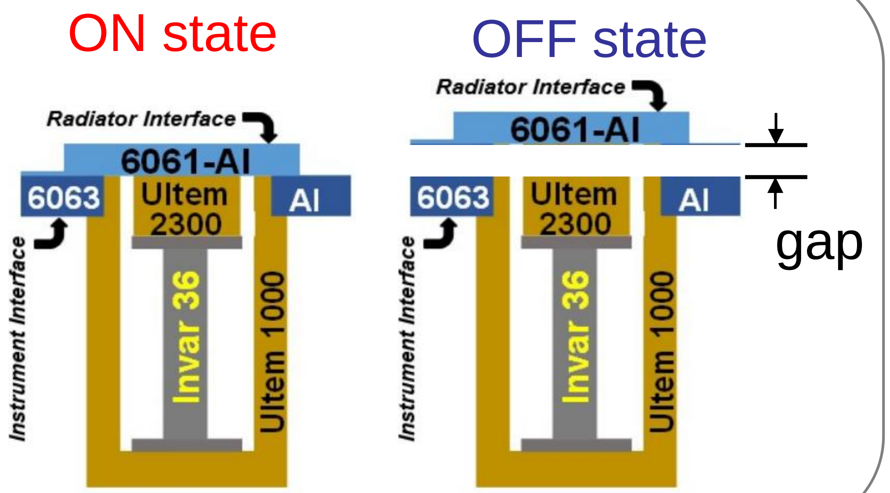
- CTE

-Switch ratio up to 2500

-High machining requirements

-Large hysteresis



Bugby, D.C., and Rivera, J.G. (2020). Ices 145, 1–10.

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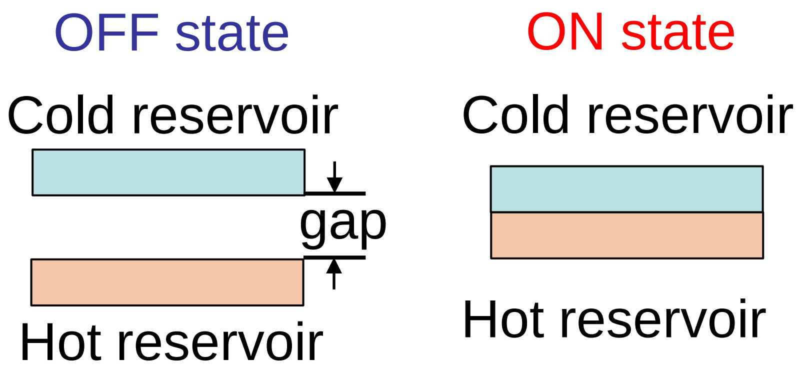

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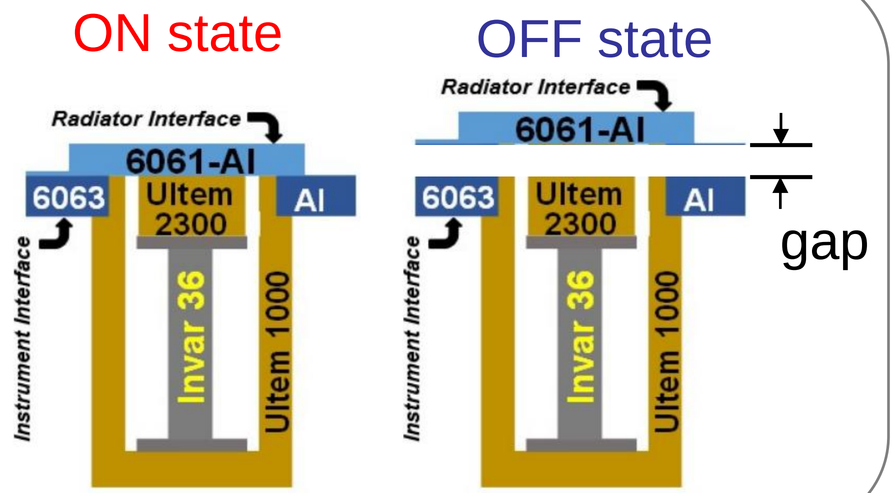
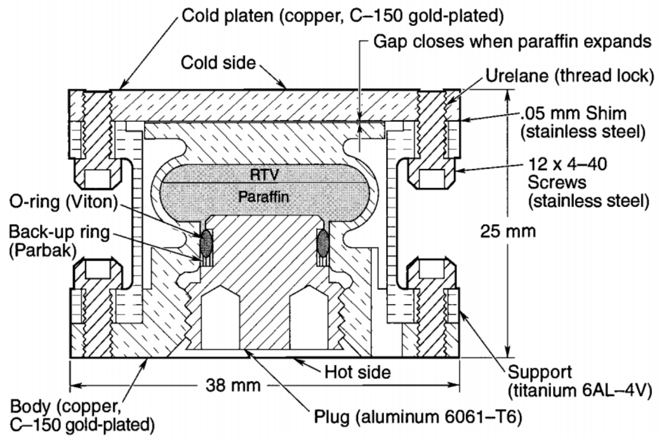


Bugby, D.C., and Rivera, J.G. (2020). Ices 145, 1–10.

- Wax expansion

-Very mature technology

-Encapsulation of wax is challenging

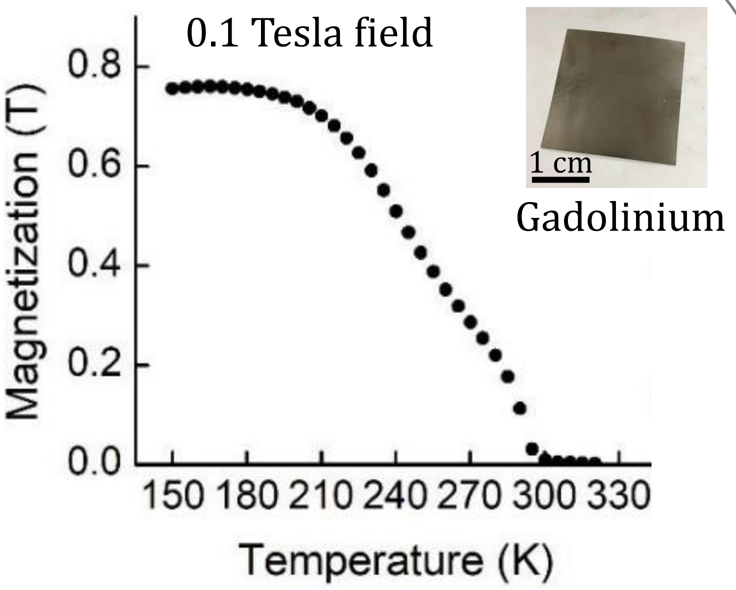


Spacecraft Thermal Control Handbook: Fundamental technologies, D.G. Gilmore. Chp. 10, "Heat Switches", K. Lankford. 2nd Ed (2002)

State-of-the-art devices are thick and have large hysteresis

Nomenclature	Switch ratio	Mass (g)	Thickness (cm)	Gap size (mm)	Thermal hysteresis (^oC)	Reference
Thermal expansion	>2000	~150	>8	<0.1	~40	Bugby, D.C., and Rivera, J.G. (2020). Ices *145*, 1–10.
Paraffin melting	~60	~150	>5	~1	40	Sunada, E., Lankford, K., Pauken, M., Novak, K.S., and Birur, G. (2002). AIP Conf Proc *608*, 211–213. 10.1063/1.1449727.

Temperature dependent magnetic forces as actuation



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- Ferromagnetic below T_{Curie} and paramagnetic above T_{Curie}

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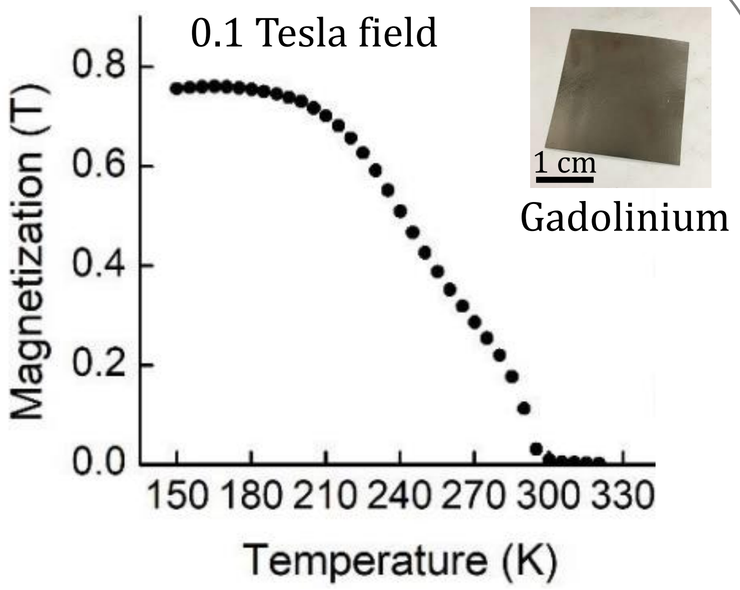

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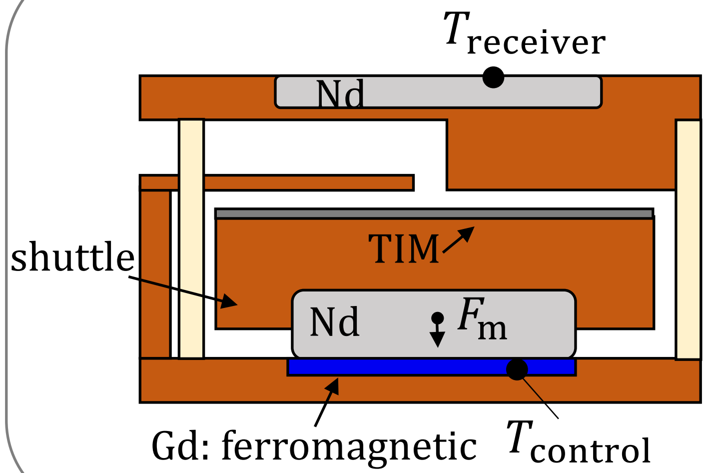

Thermal regulator OFF state

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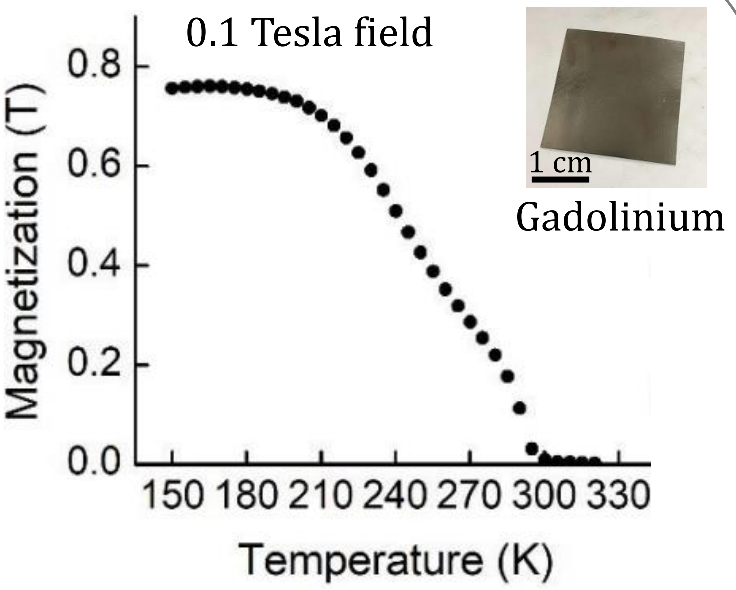

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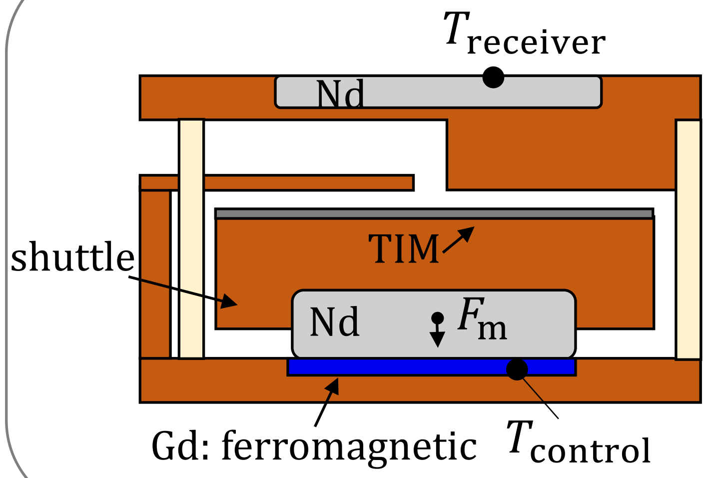

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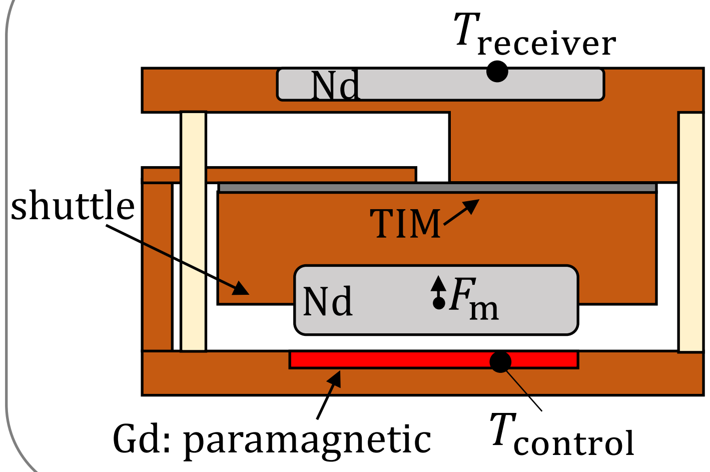

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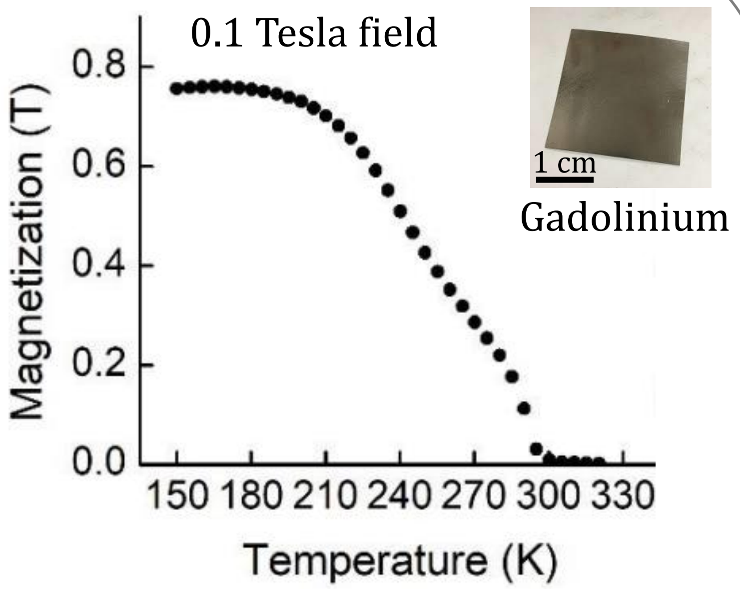

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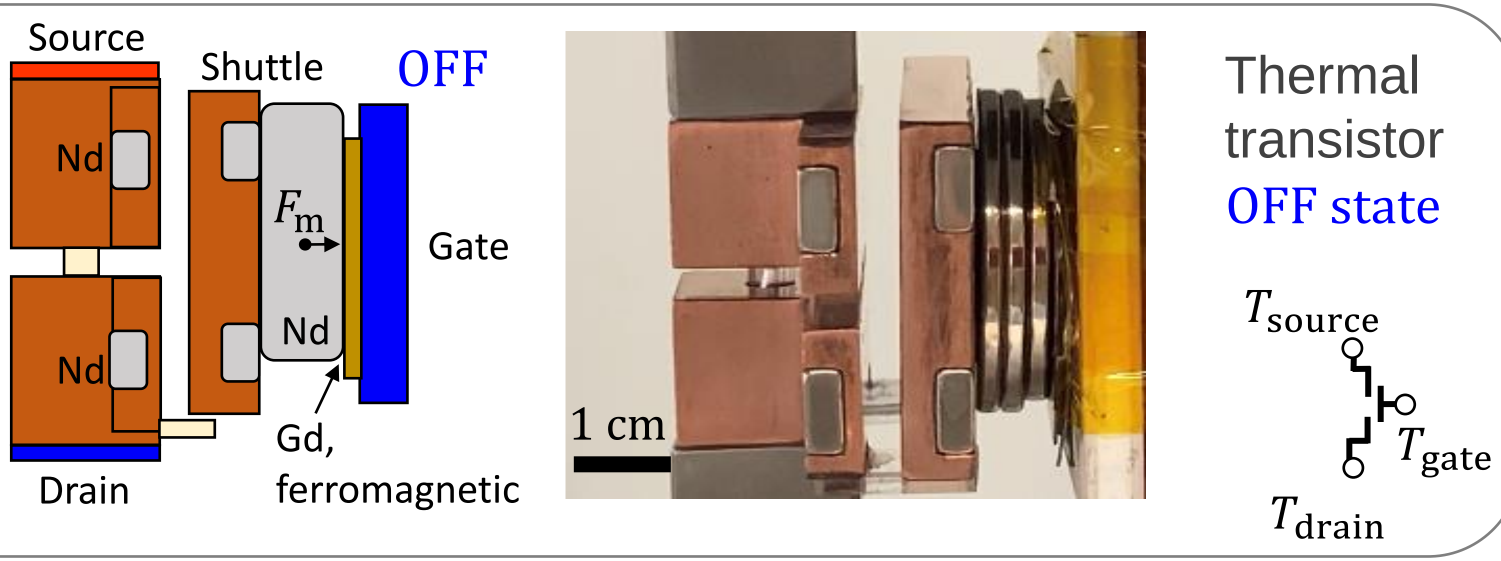

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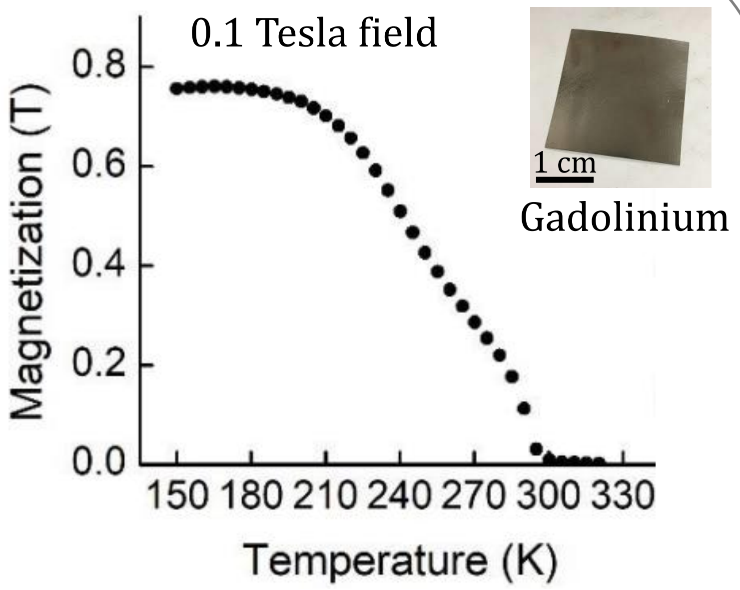

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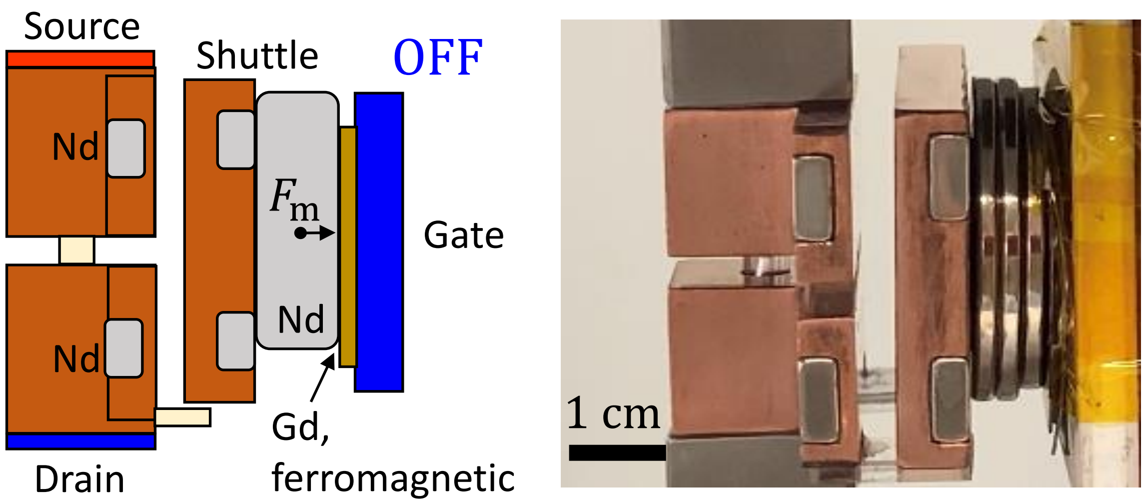
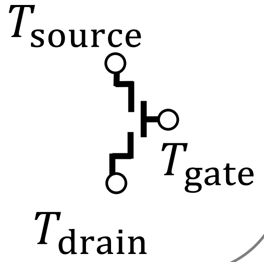
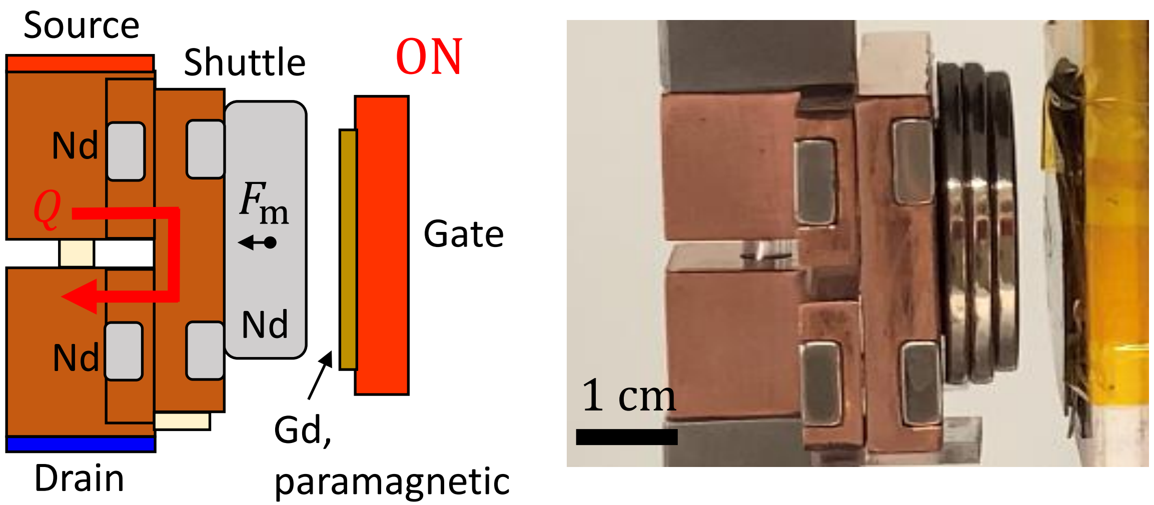


Thermal transistor OFF state





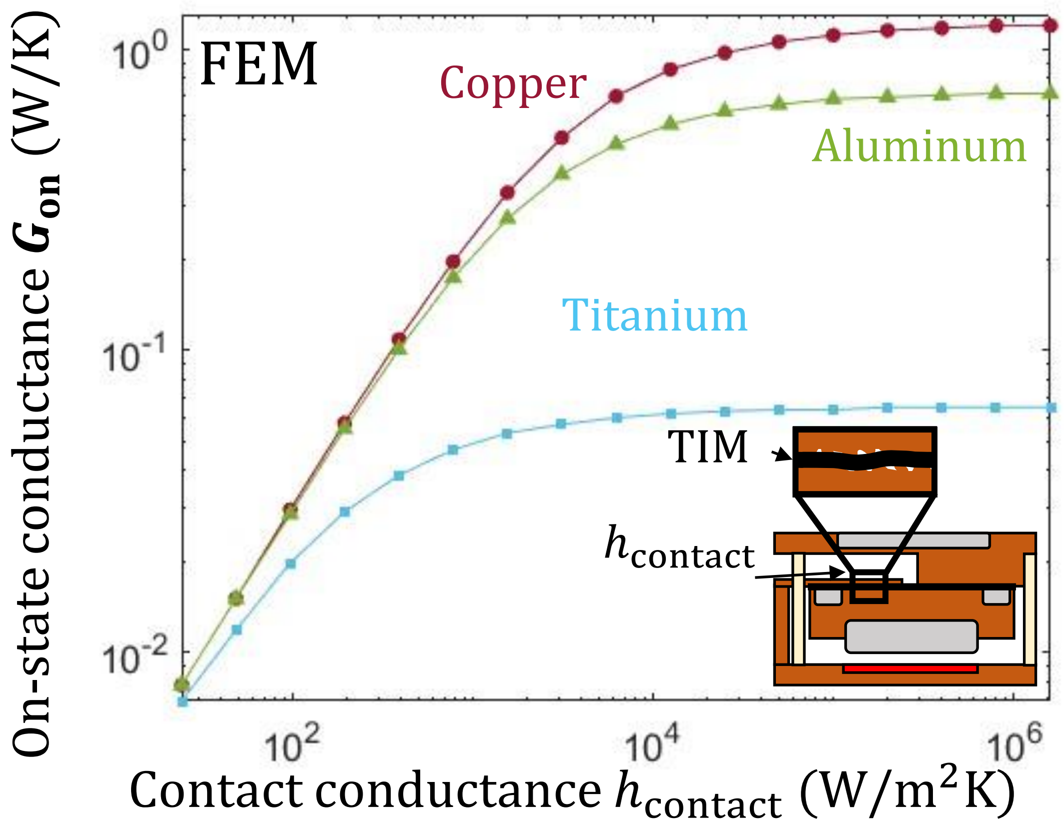
Thermal transistor ON state

Switching is activated by temperature change

Thermal regulator

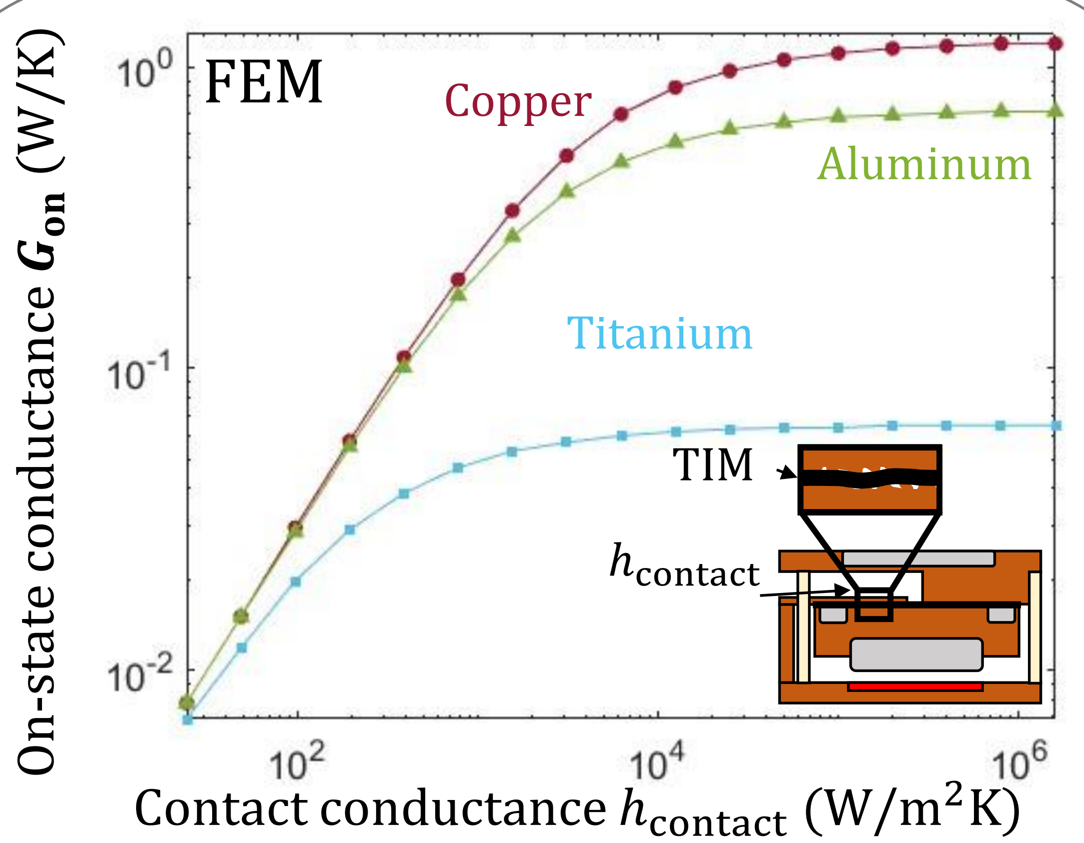
Thermal transistor

ON state depends largely on contact conductance



- Design was informed by heat transfer and magnetostatic FEM calculations
- Aim was to achieve NASA requirements

OFF state depends largely on radiation across gap



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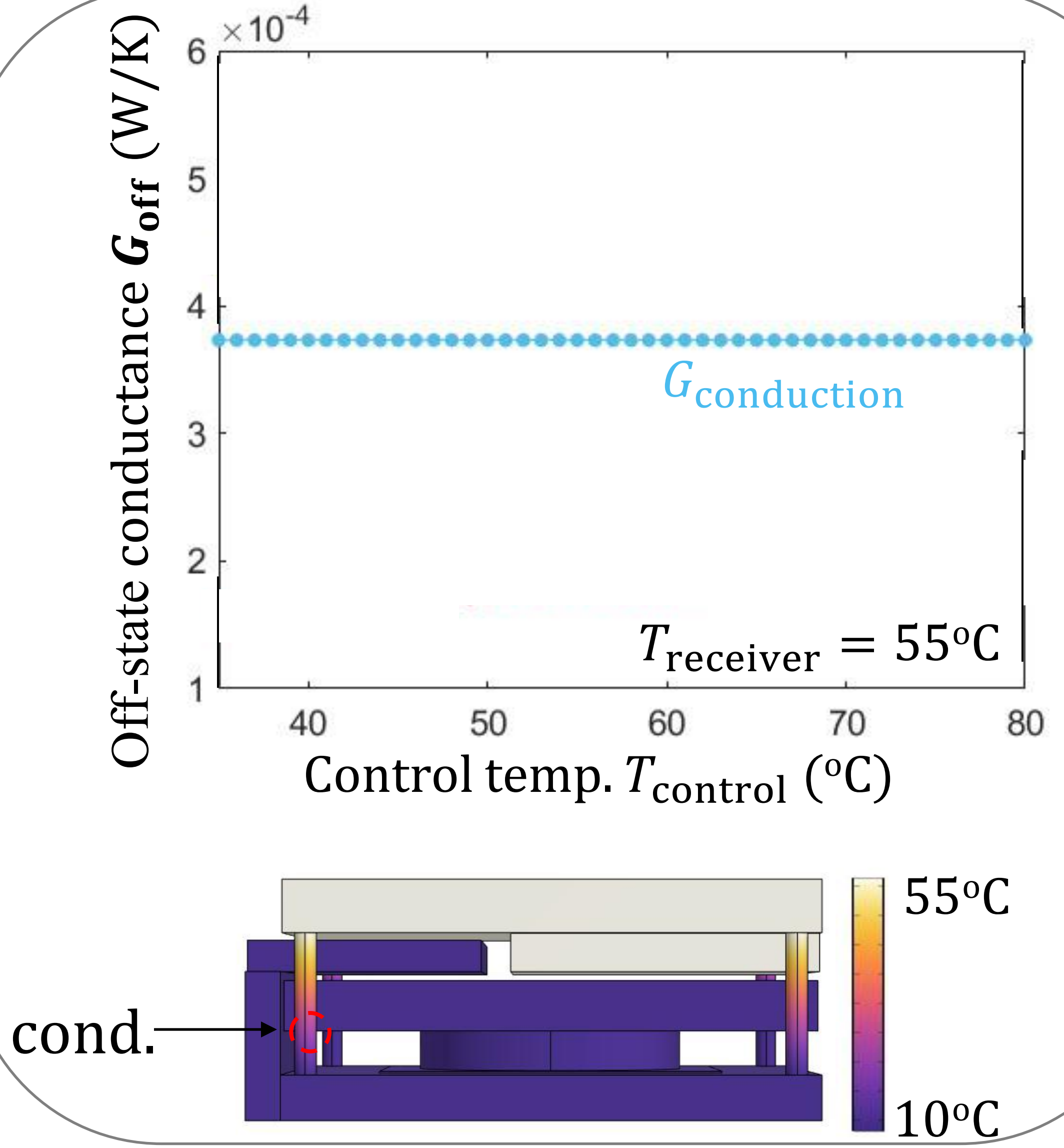

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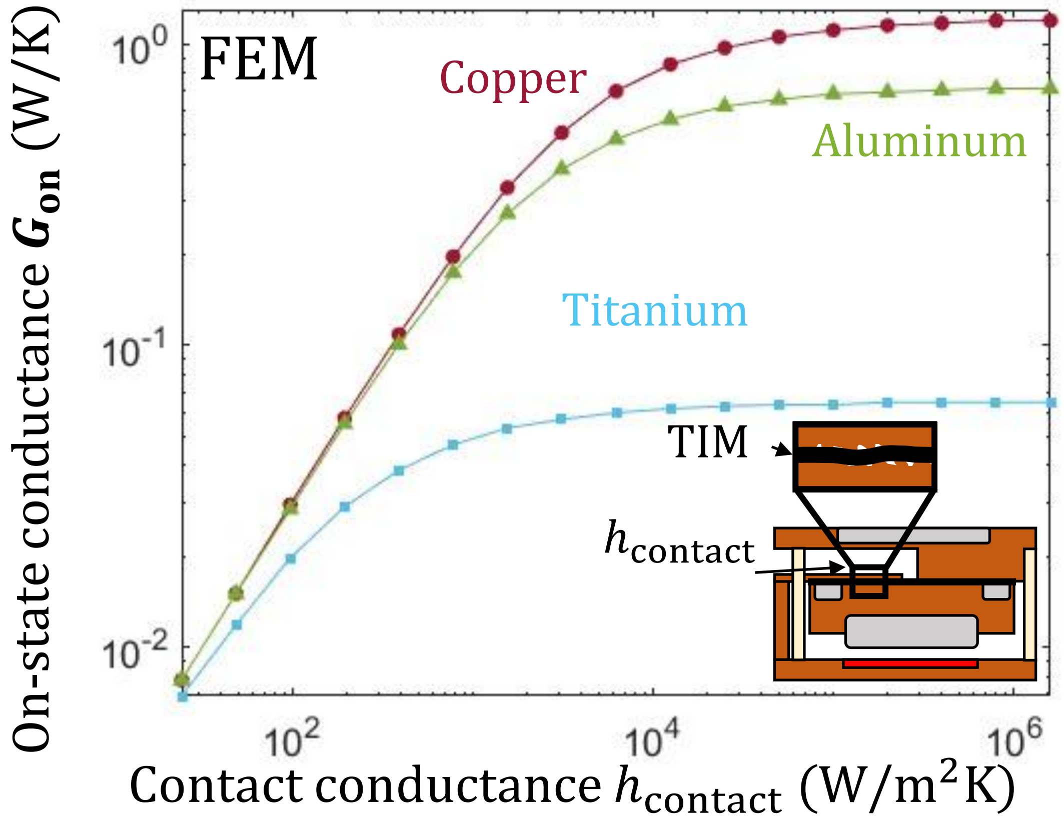

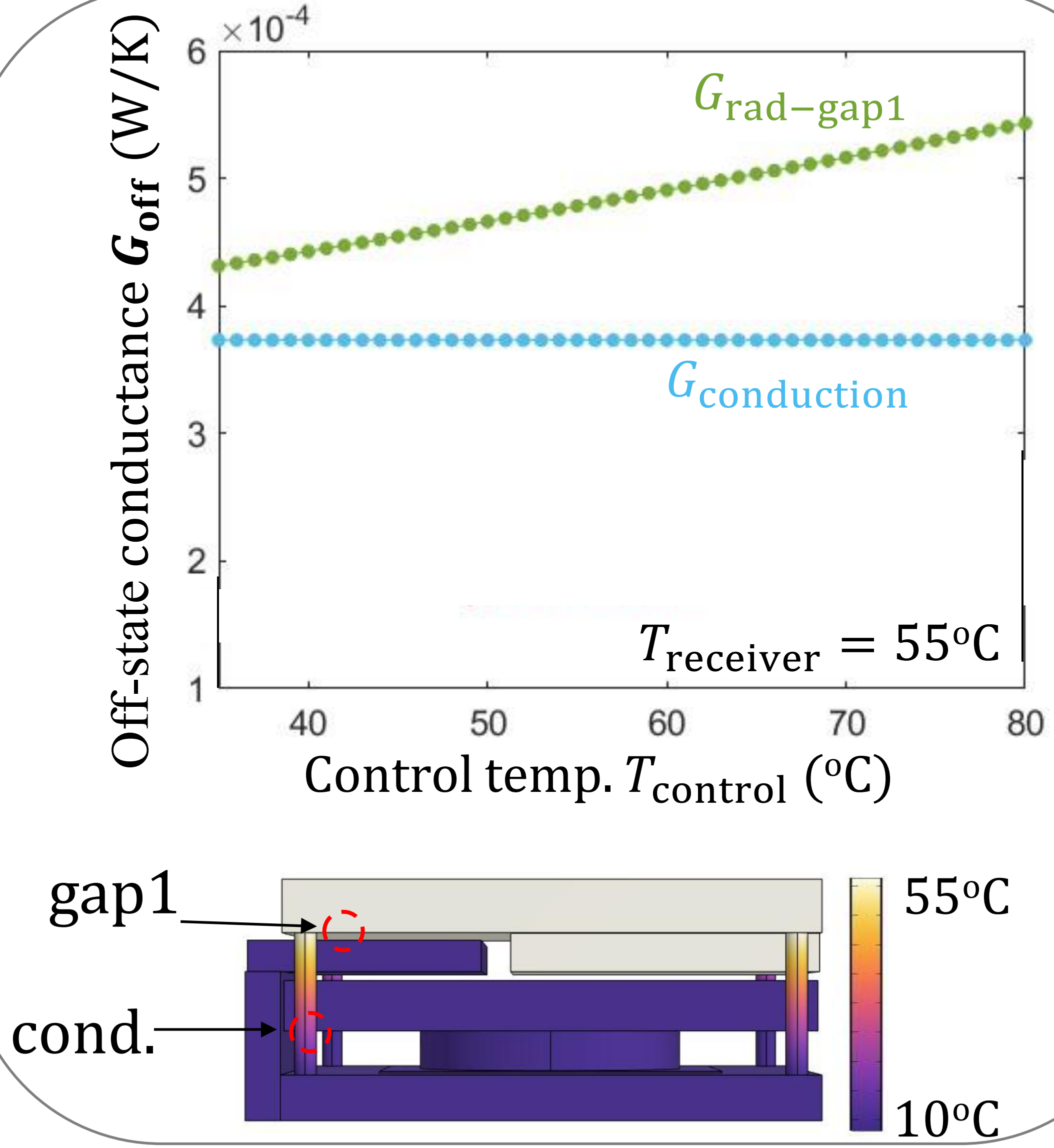

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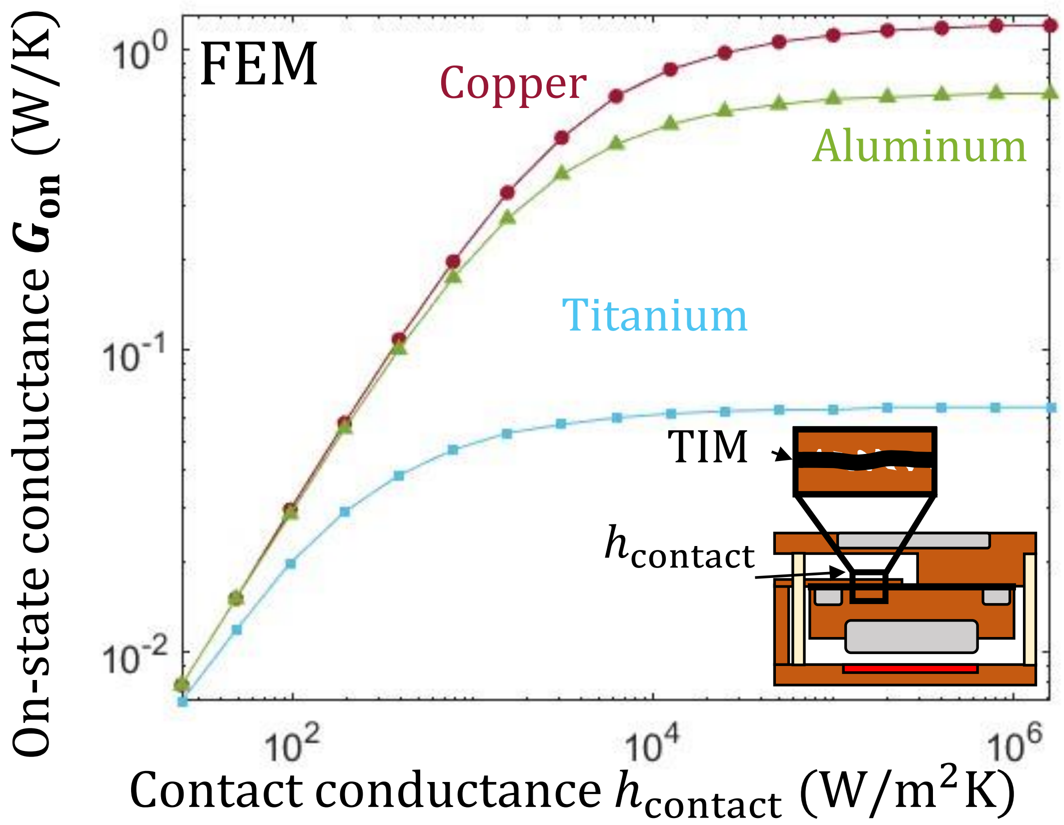

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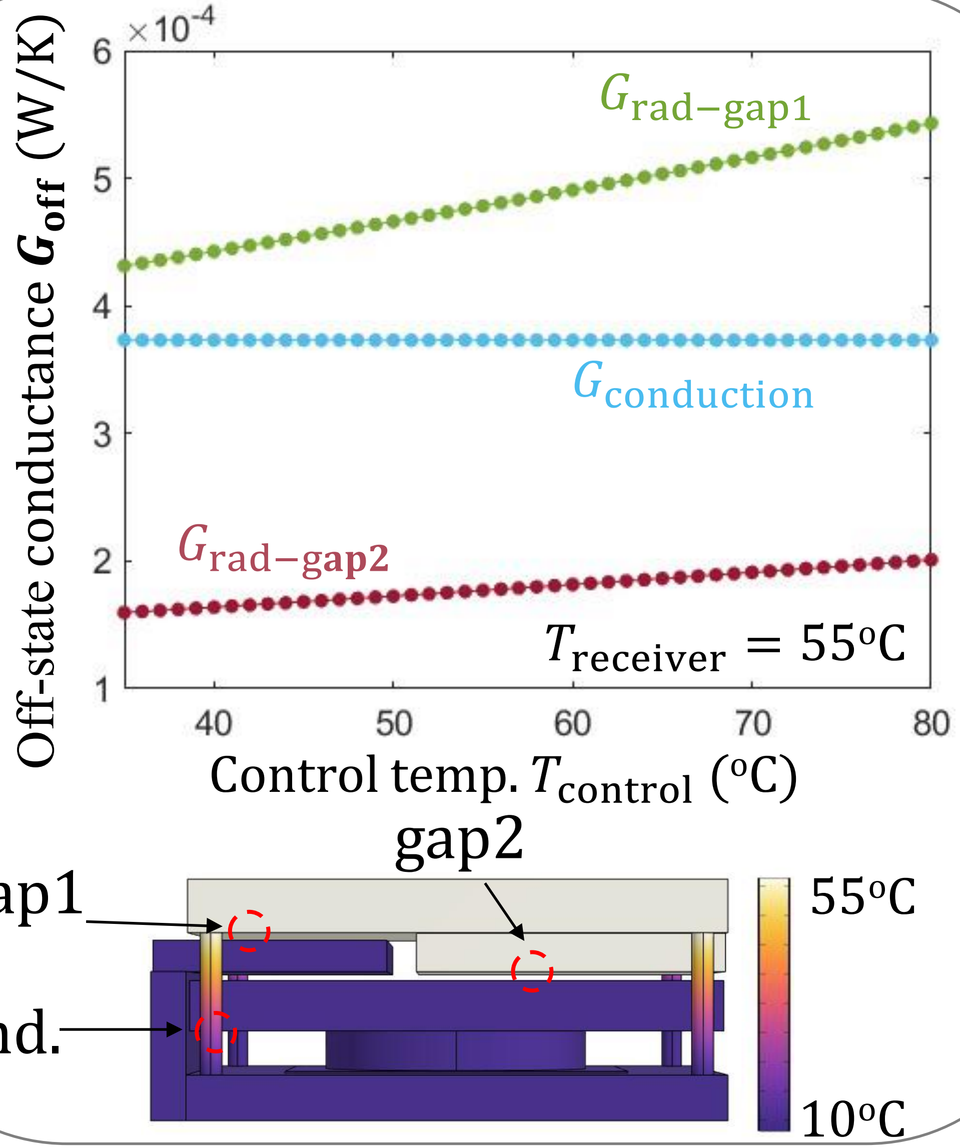
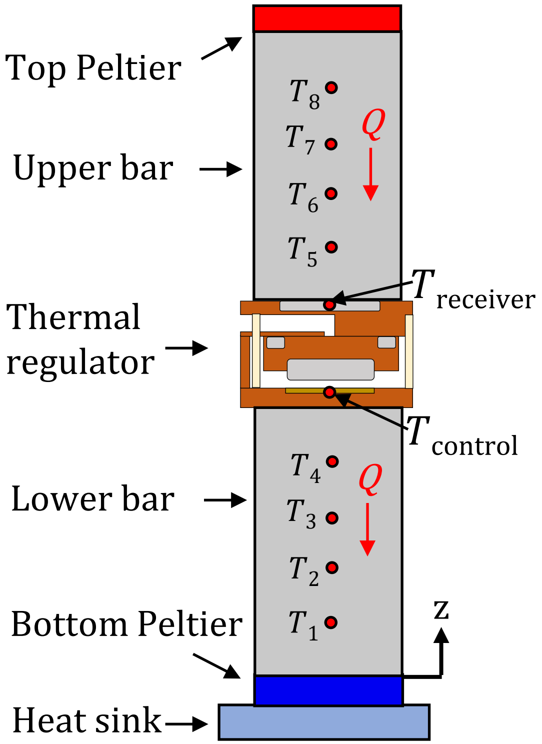


Reference bar apparatus to measure heat flow

Reference bar apparatus



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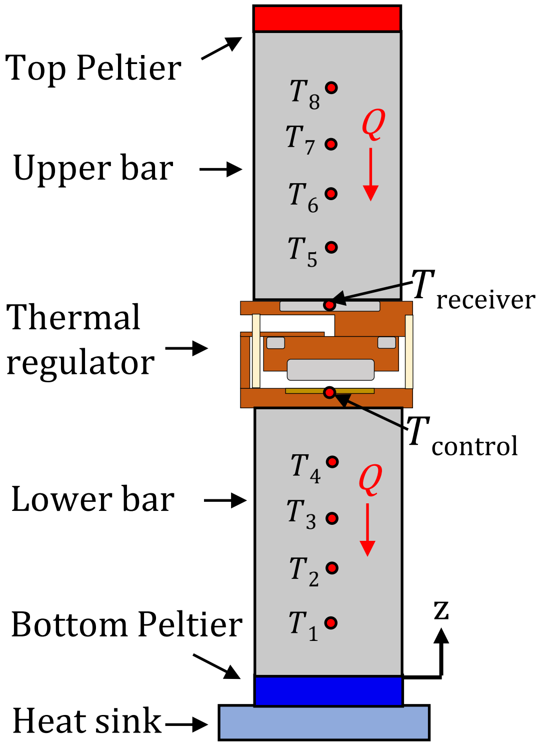
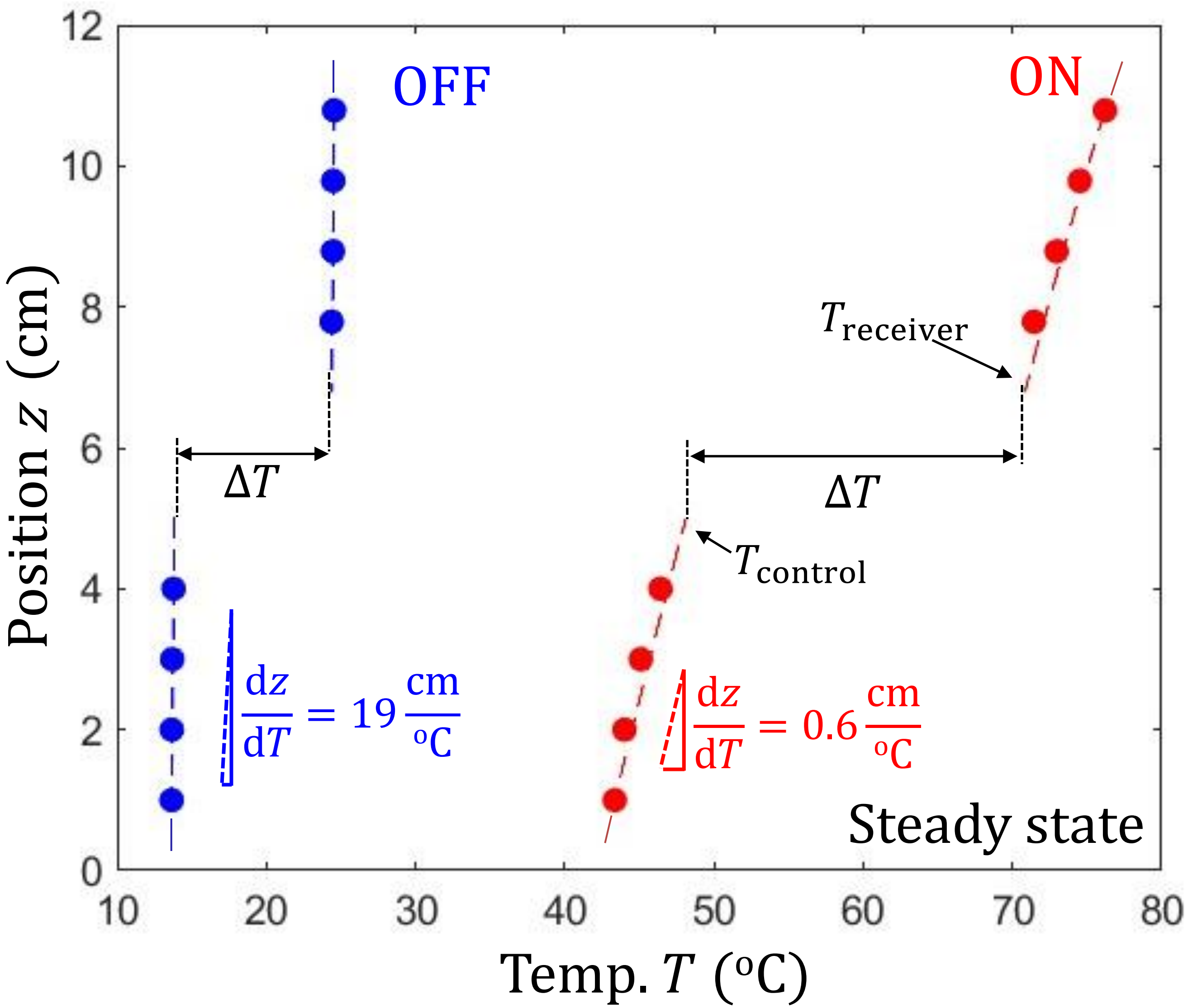
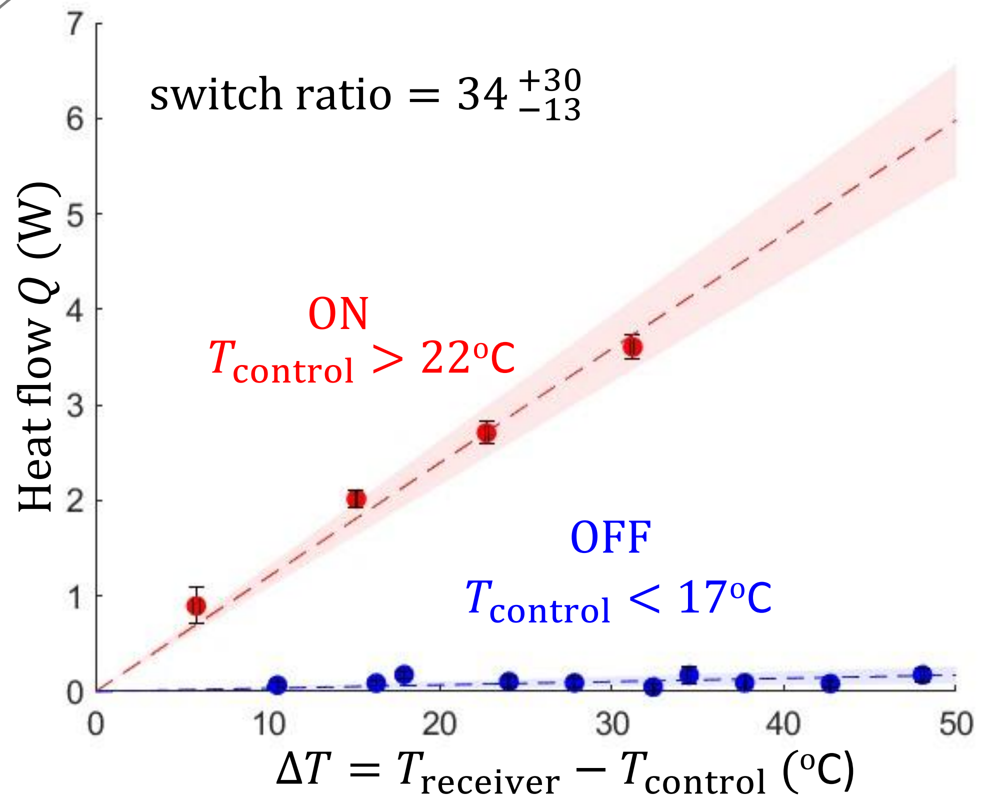




Both devices exhibit good thermal switching in vacuum



Thermal regulator

$G_{\text{on}} = 0.12$ W/K

$G_{\text{off}} = 0.0035$ W/K

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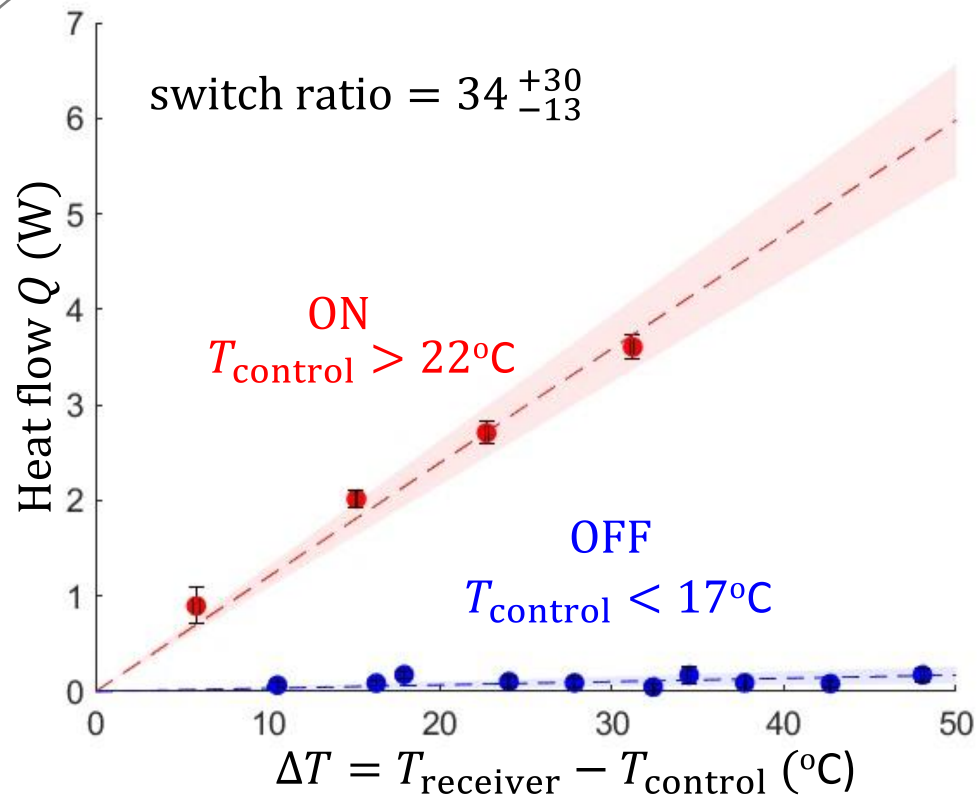

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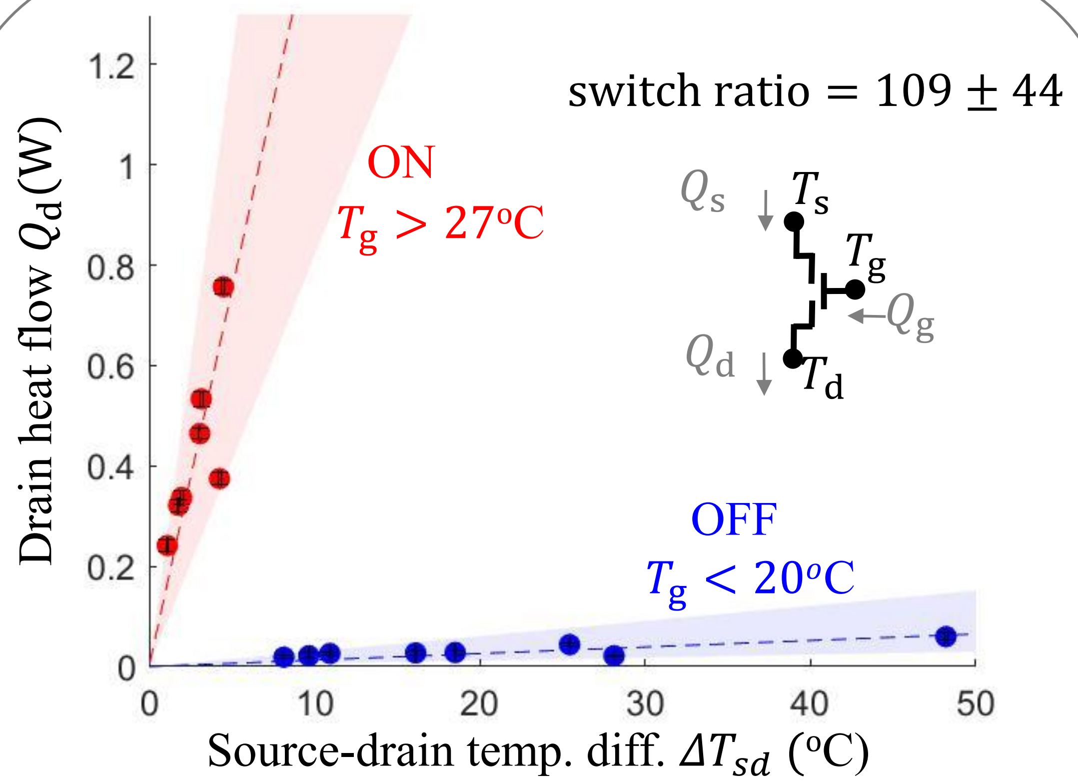
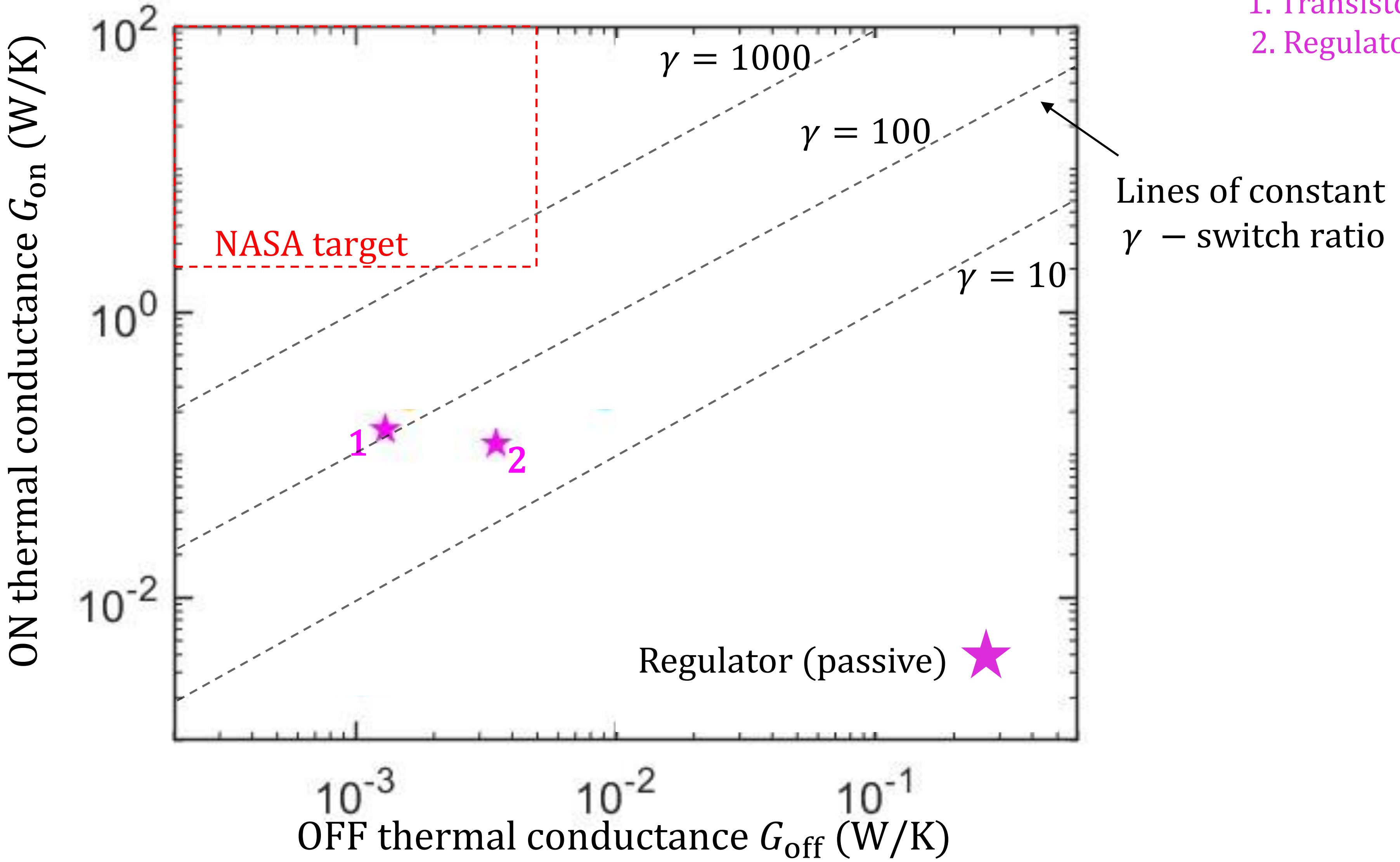


Thermal transistor $G_{\text{on}} = 0.15$ W/K

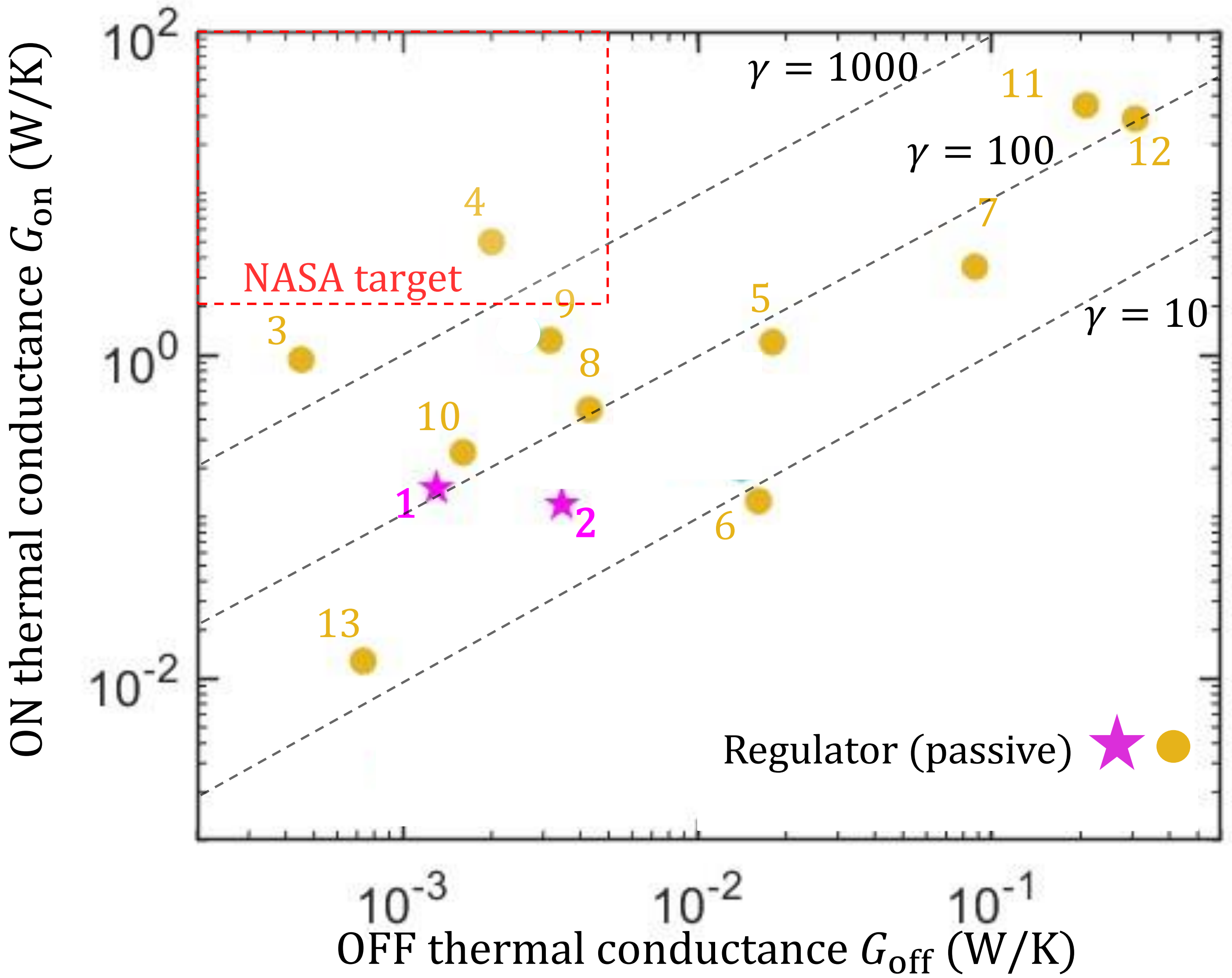
$G_{\text{off}} = 0.0013$ W/K

Thermal conductance comparison



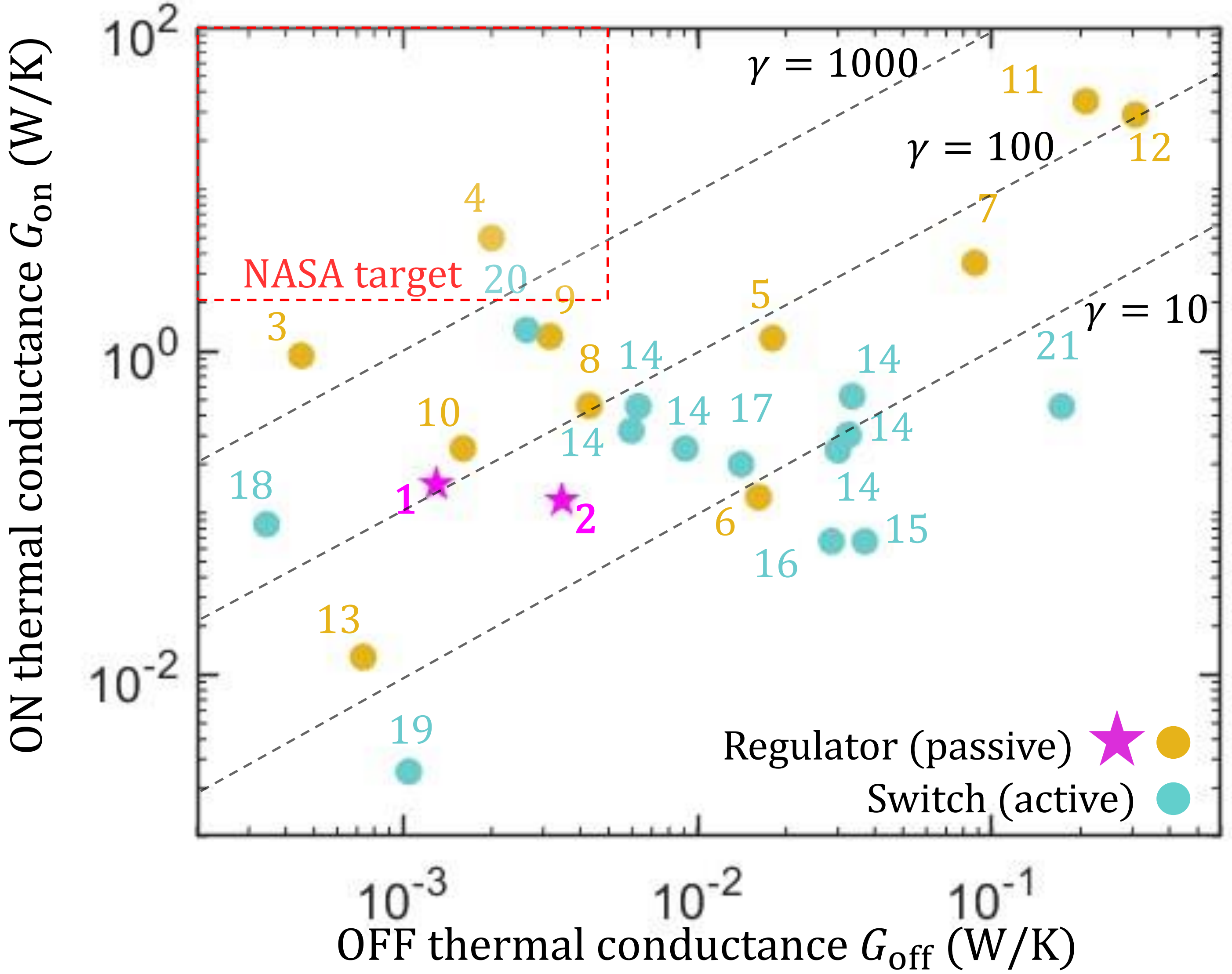
1. Transistor
2. Regulator

Thermal conductance comparison



1. Transistor
2. Regulator
3. SMA 1 vacuum
4. JPL-CTE
5. JPL-paraffin
6. Ti_CTE
7. SMA 1 air
8. MiSER
9. CTE 1
10. CTE 2
11. VHCP
12. SMA 2
13. Paraffin motor

Thermal conductance comparison



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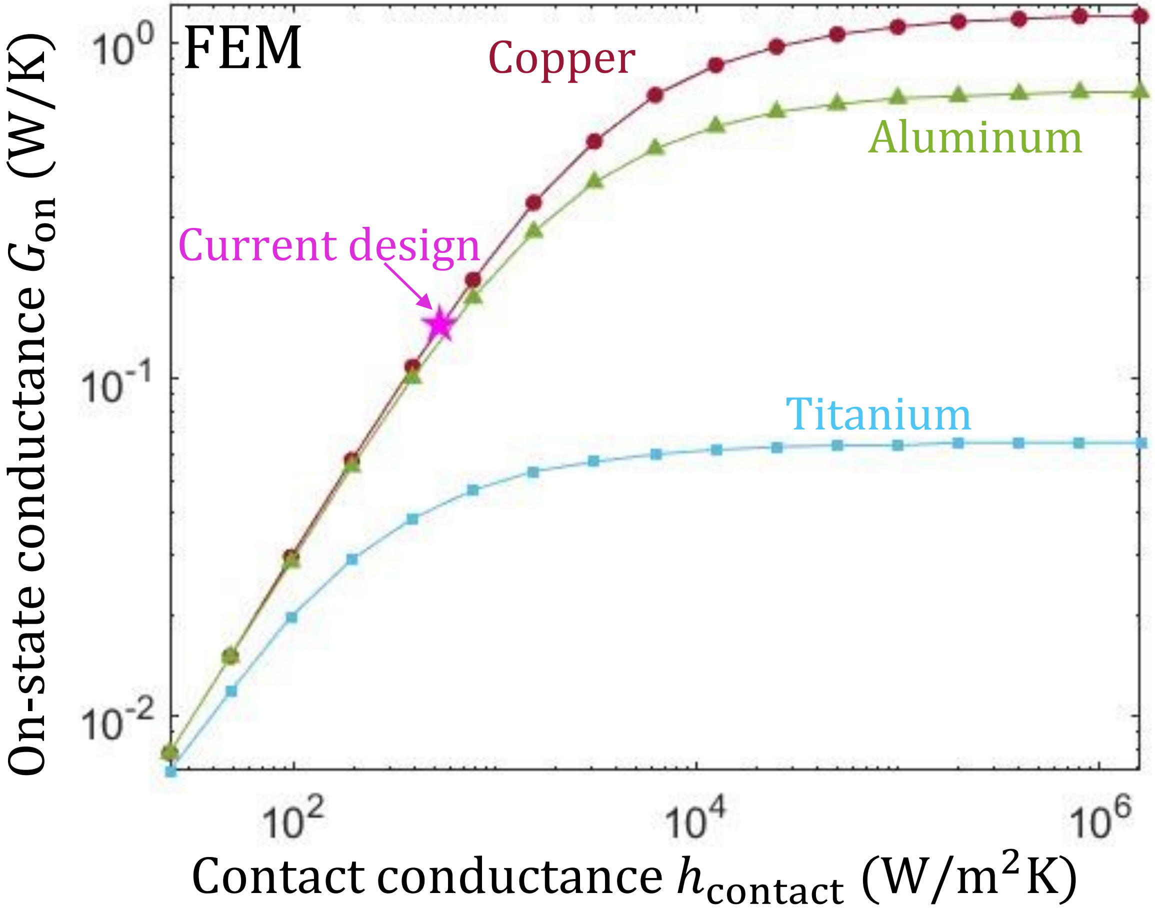
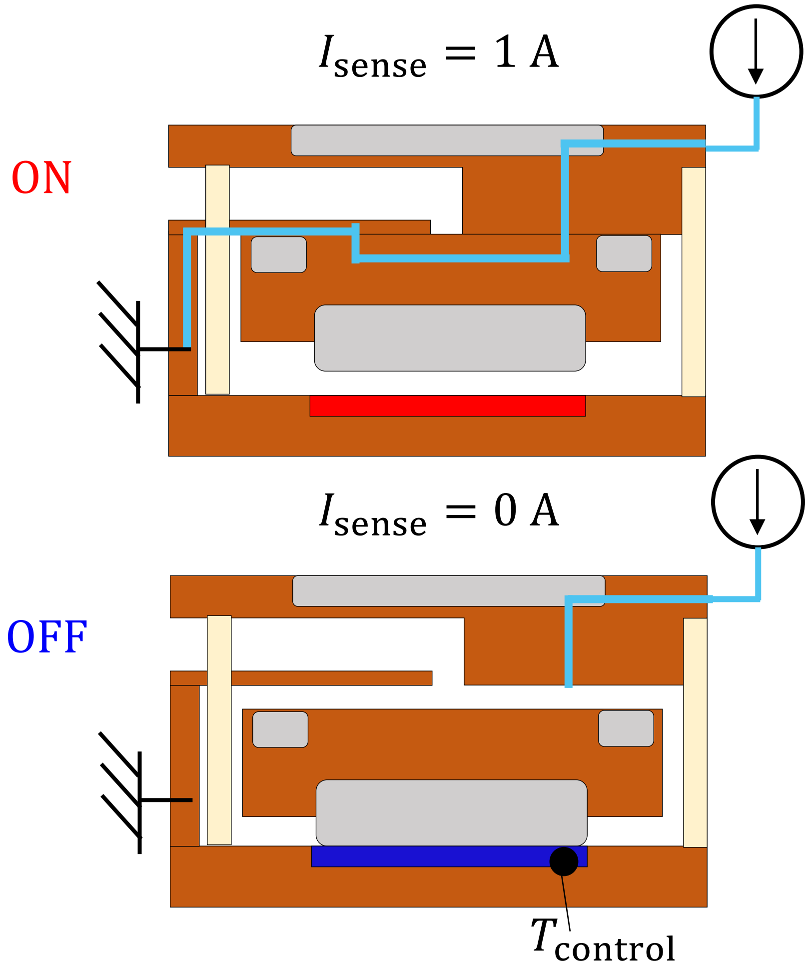
14. Liquid metal
15. Wet channel droplet
16. Dry channel droplet
17. EWOD 1
18. Gas gap 1
19. EWOD 2
20. Gas gap 2
21. Phase change



- Increasing the magnetic forces in the ON state would improve the contact pressure and G_{on}
- Improving the surface alignment between the receiver and control terminal would prevent macroscopic gaps
- Exploring other choices of TIM materials might improve the h_{contact}

>1000 repeatable switching cycles



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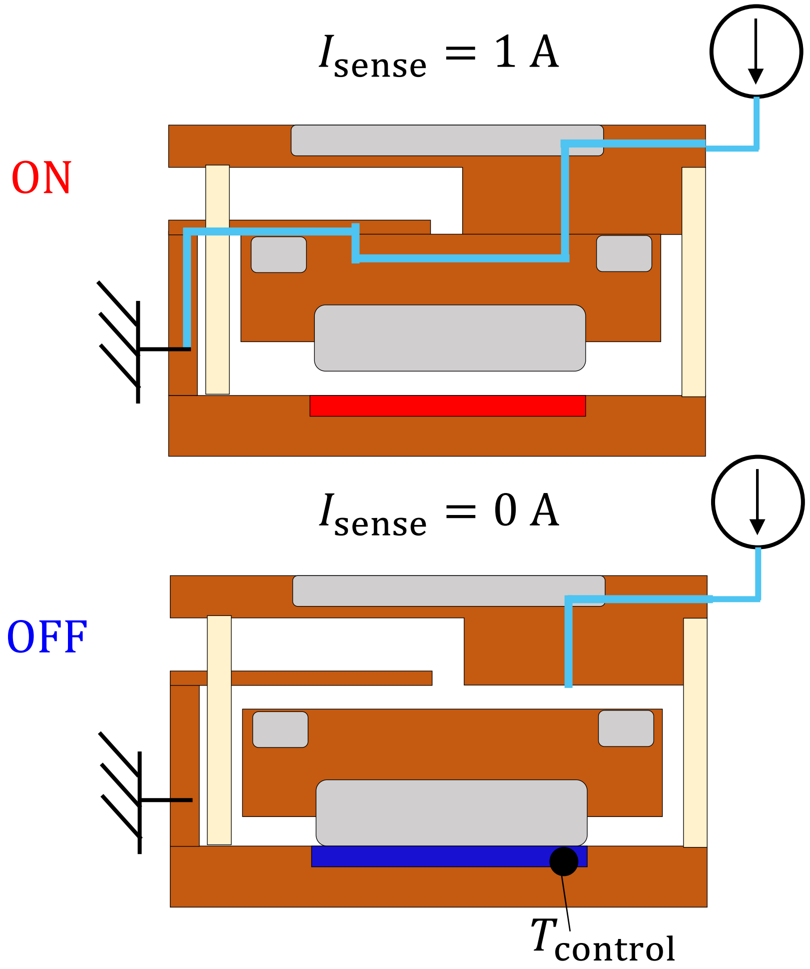
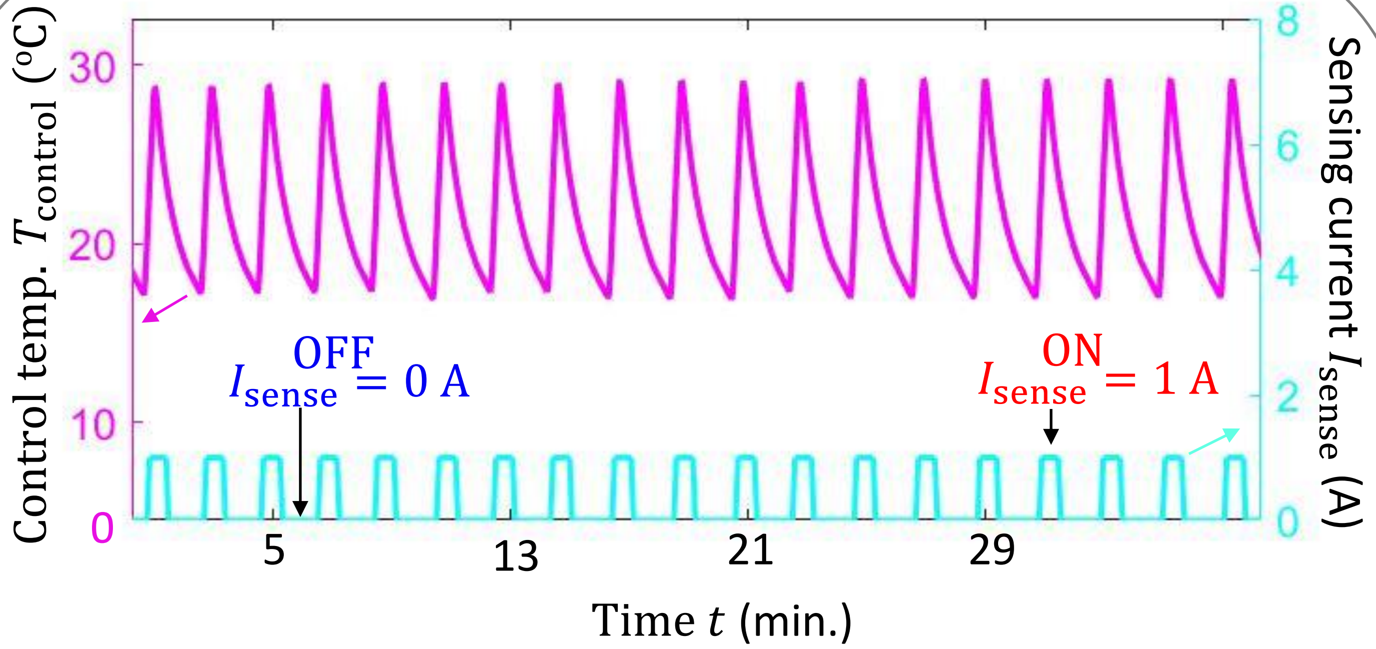
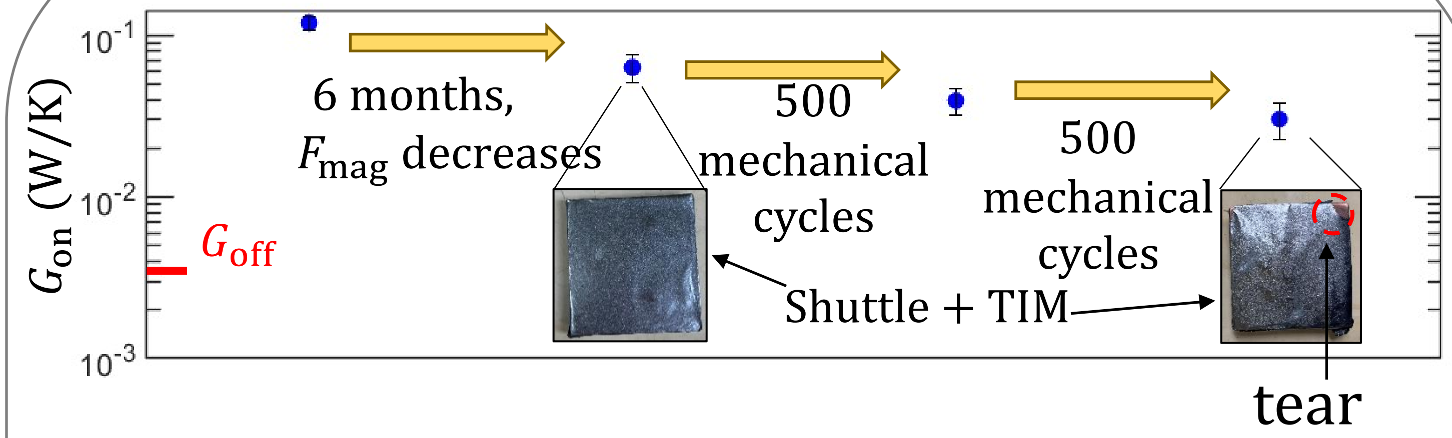




-Both devices switched reversibly over 1000 cycles

-Reliable actuation for lab scale demonstrations

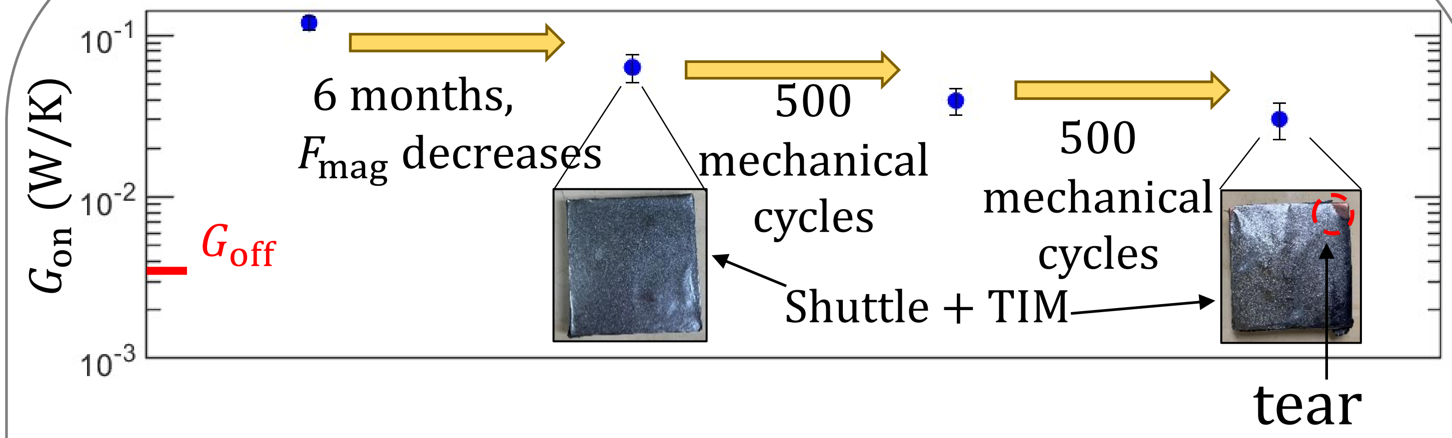
Decrease in ON state performance observed over time



-Degradation is due to loss in magnetic strength over time and due to exposure to elevated temperature (>70ºC)

-Thermal interface material (TIM) degrades after extended cycling

Magnetic mechanism has small thermal hysteresis



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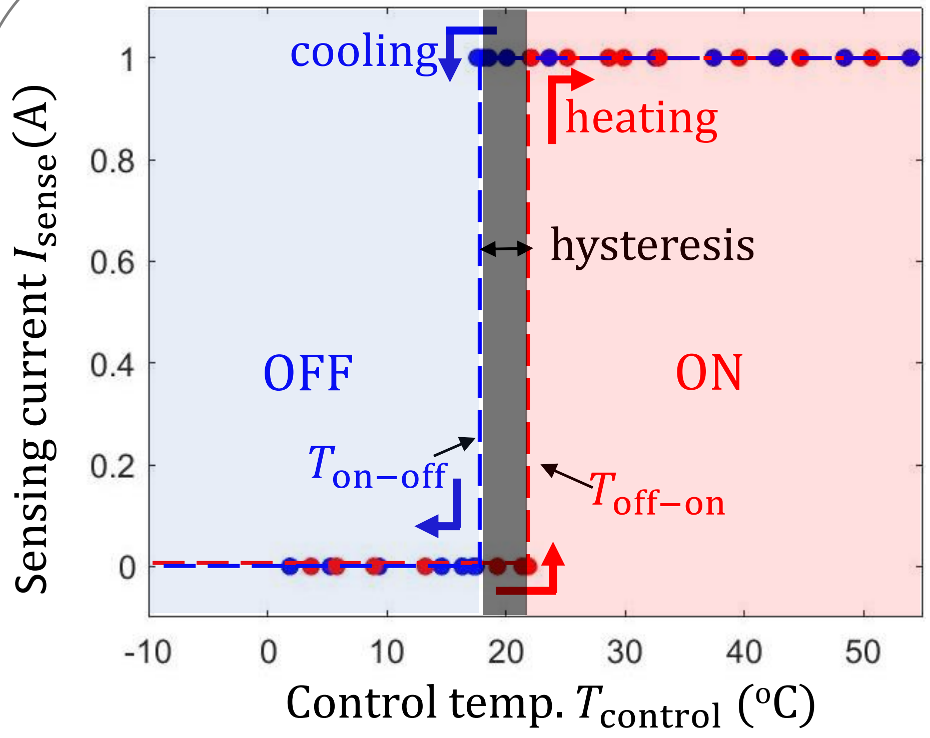


Thermal regulator

$T_{off-on} = 17°C$

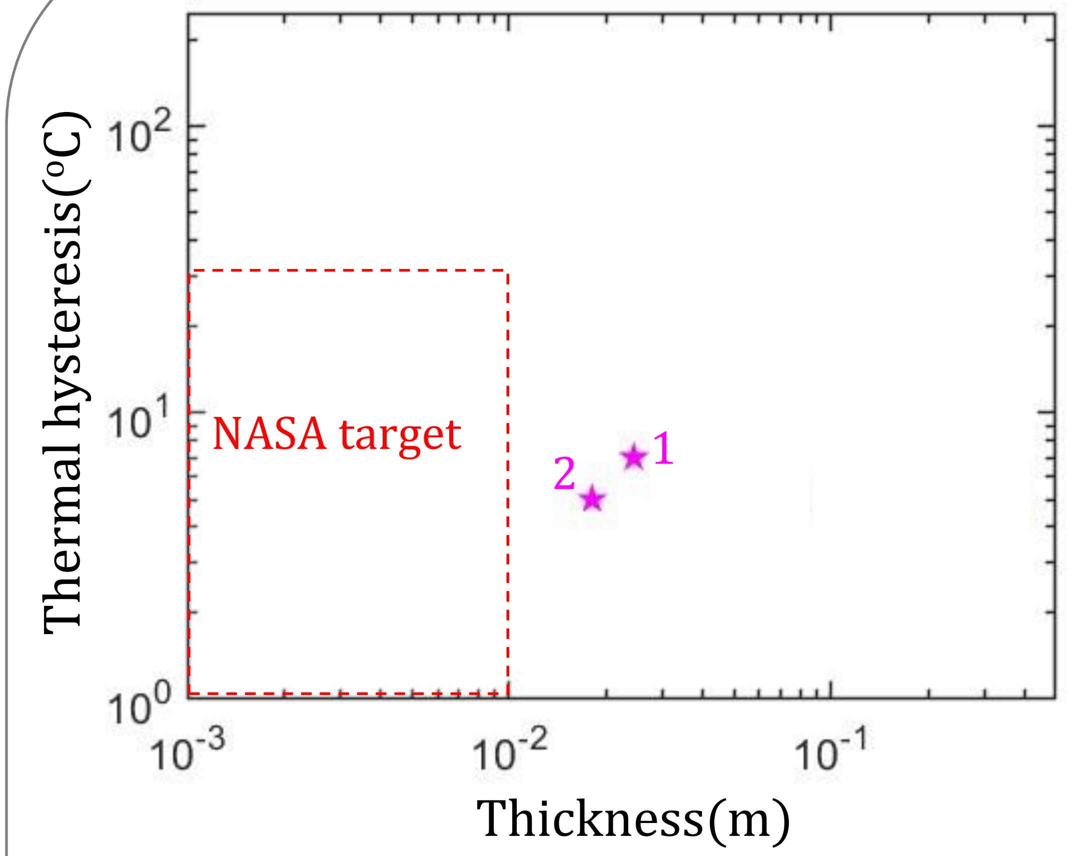
$T_{on-off} = 22°C$

Thermal transistor

$T_{off-on} = 20°C$

$T_{on-off} = 27°C$

Thin devices with small hysteresis



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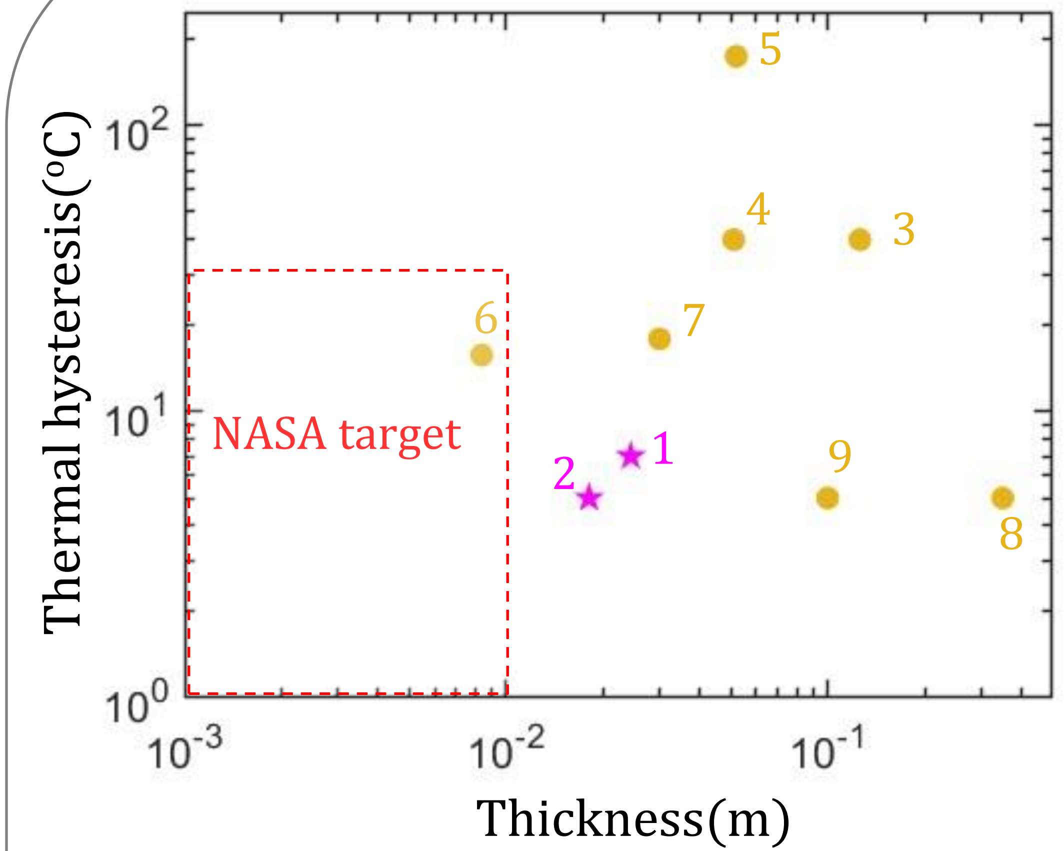

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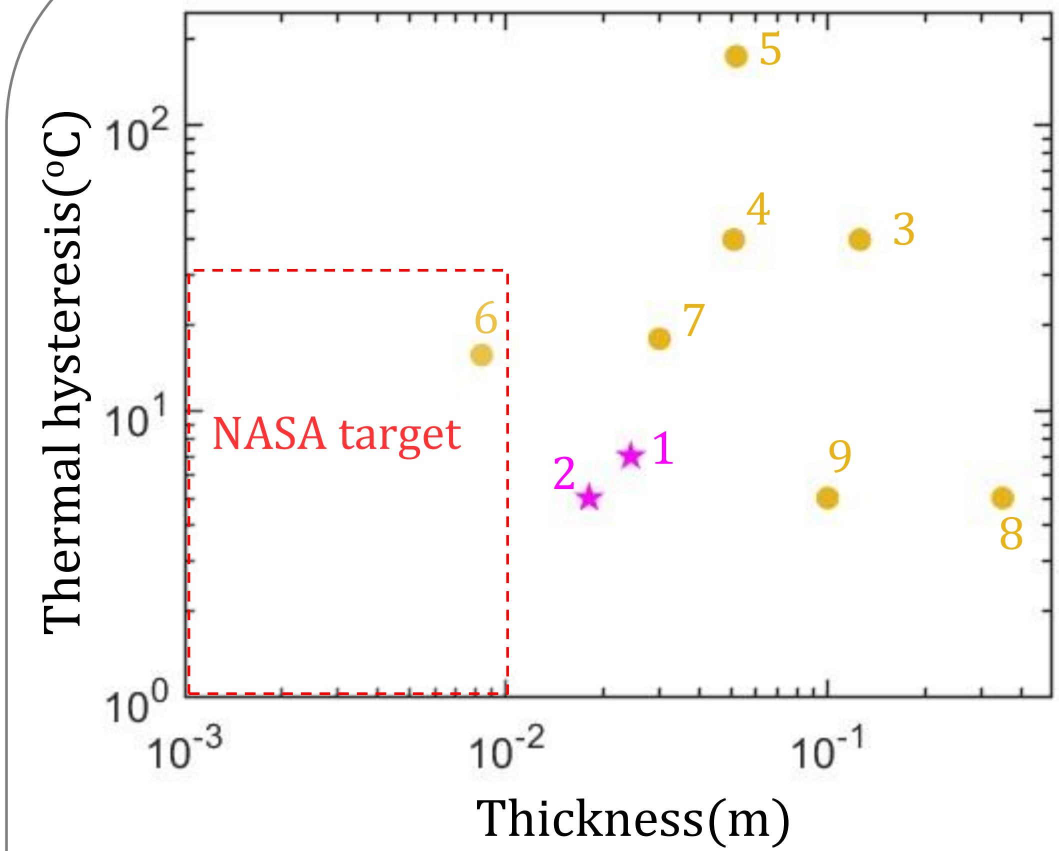
-Hysteresis and thickness are small compared to most devices

Thin devices with small hysteresis



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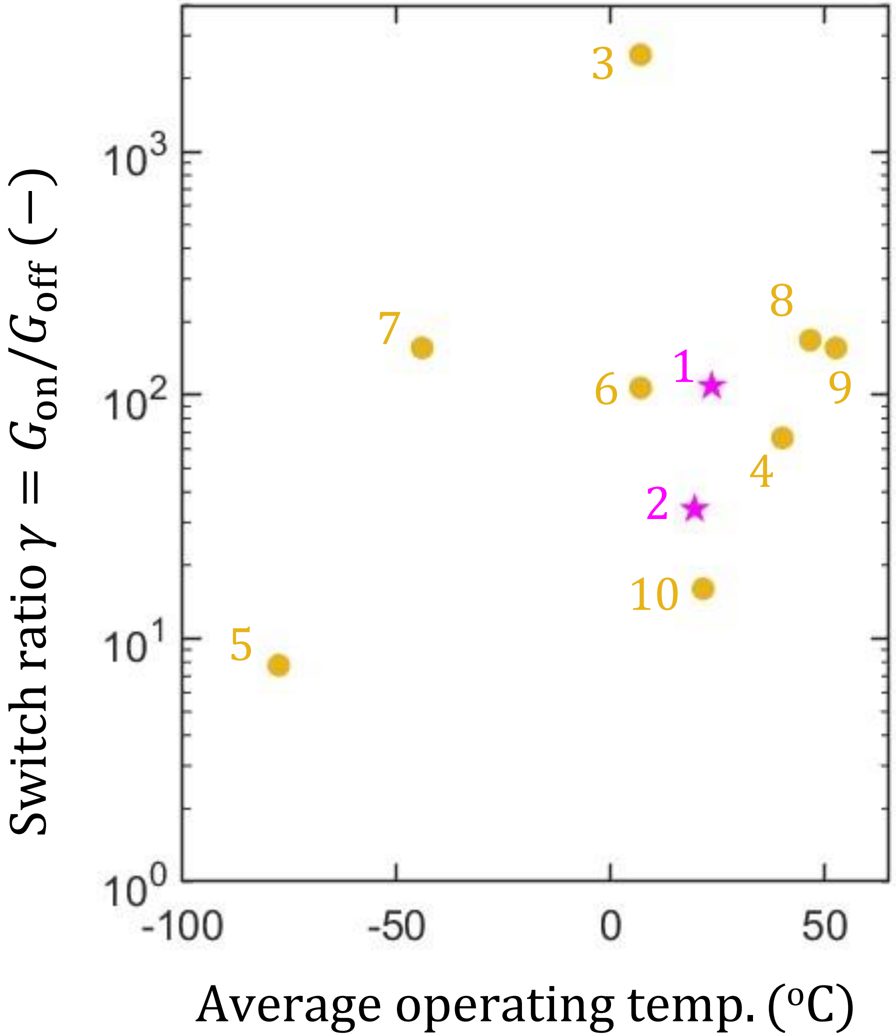
10. SMA 1 Air

-Hysteresis and thickness are small compared to most devices

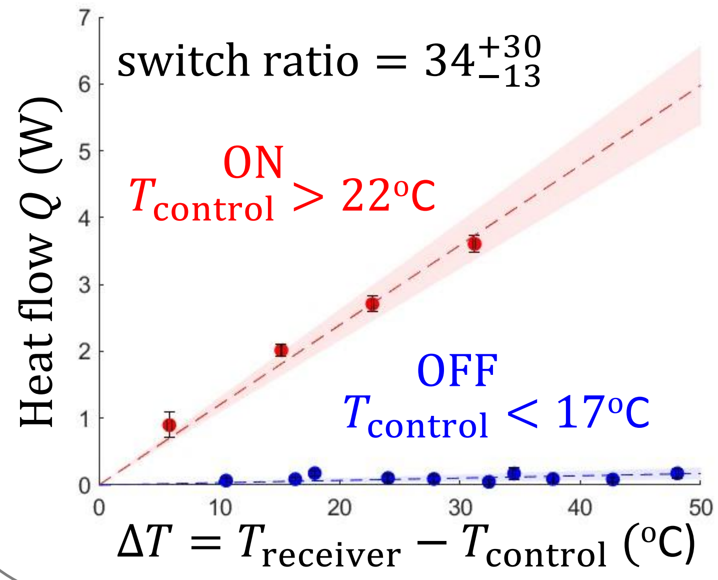


Final comparison with state-of-the-art

Nomenclature	Switch ratio	Mass (g)	Thickness (cm)	Gap size (mm)	Thermal hysteresis (°C)	Reference
Thermal expansion	>2000	~150	>8	<0.1	~40	Bugby, D.C., and Rivera, J.G. (2020). Ices *145*, 1–10.
Paraffin melting	~60	~150	>5	~1	40	Sunada, E., Lankford, K., Pauken, M., Novak, K.S., and Birur, G. (2002). AIP Conf Proc *608*, 211–213. 10.1063/1.1449727.
Magnetic transistor	109	114	2.4	~1	7	Castelli, L., Zhu, Q., Shimokusu, T.J., and Wehmeyer, G. (2023). Nat Commun 14, 36056. 10.1038/s41467-023-36056-4.
Magnetic regulator	34	192	1.8	~1	5	Castelli, L., Garg, A., Zhu, Q., Sashital, P., Shimokusu, T.J., and Wehmeyer, G. (2023). A thermal regulator using passive all-magnetic actuation. Cell Reports Physical Science, Accepted

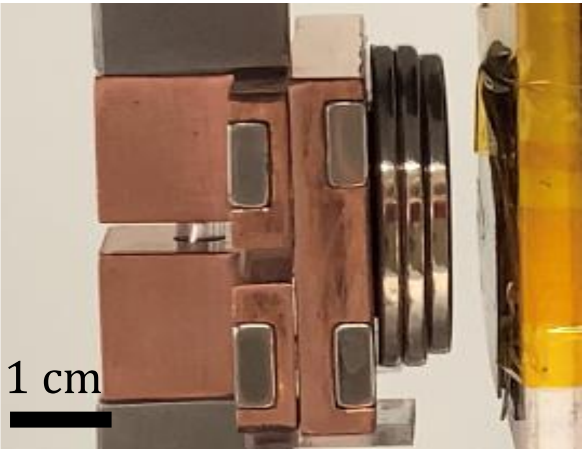
Conclusion

- Magnetically actuated transistor and regulator have switching ratio of 109 and 34 in vacuum respectively
- Hysteresis is around 5°C, small compared to other thermal regulators
- Devices reliably achieve over 1000 switching cycles



Thermal regulator

Thermal transistor



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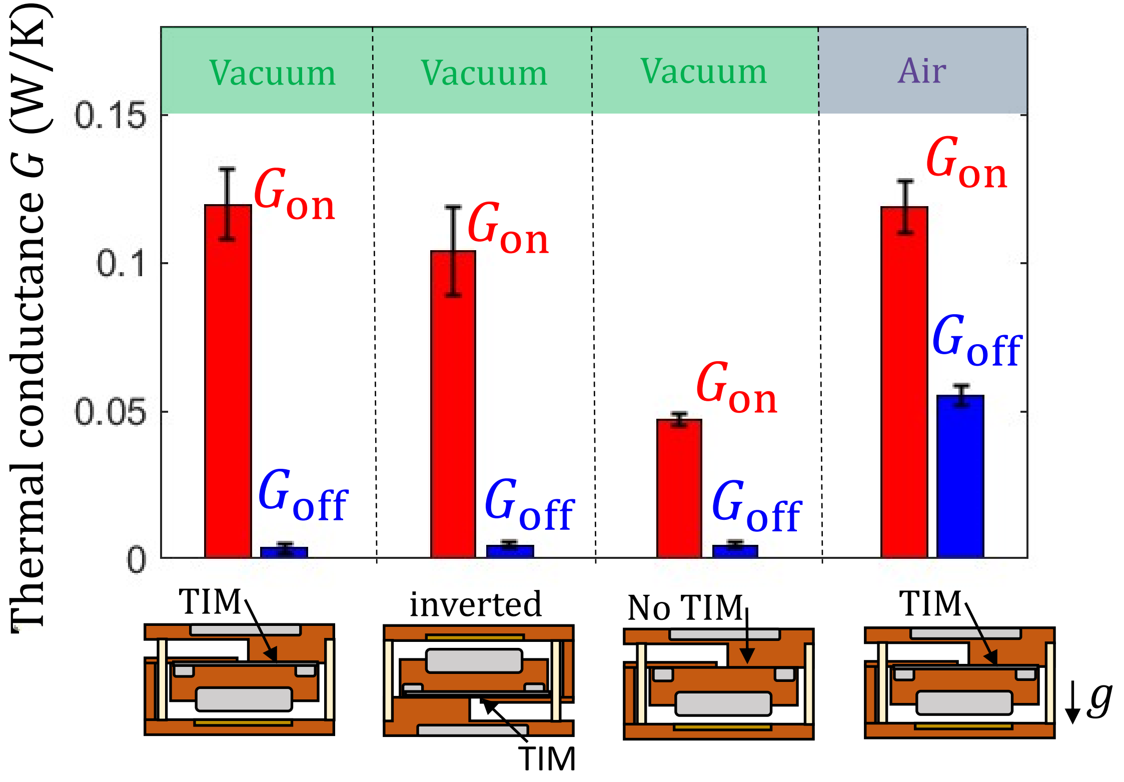
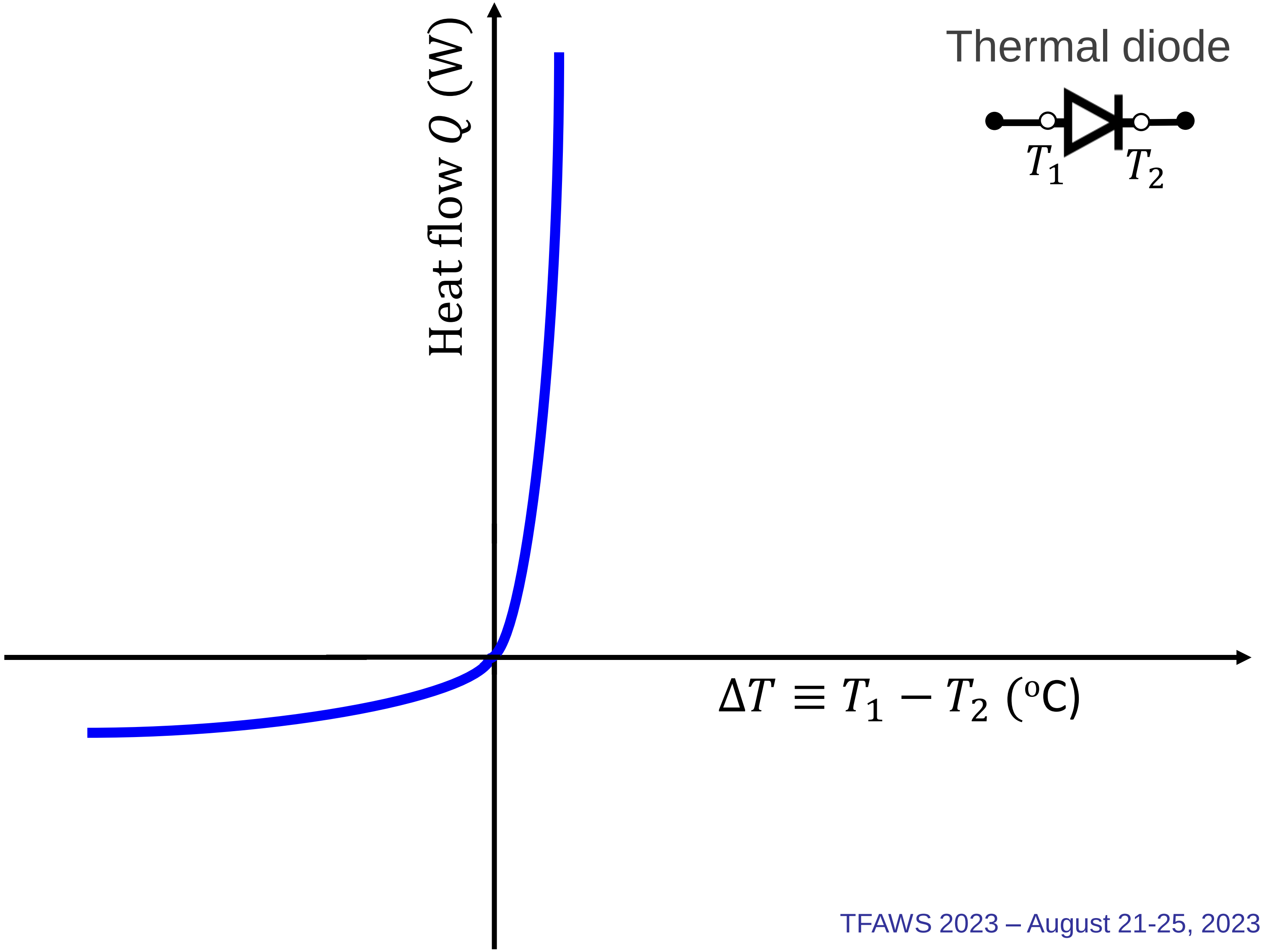
Backup Slides

Use of TIM and air environment largely affect conductance

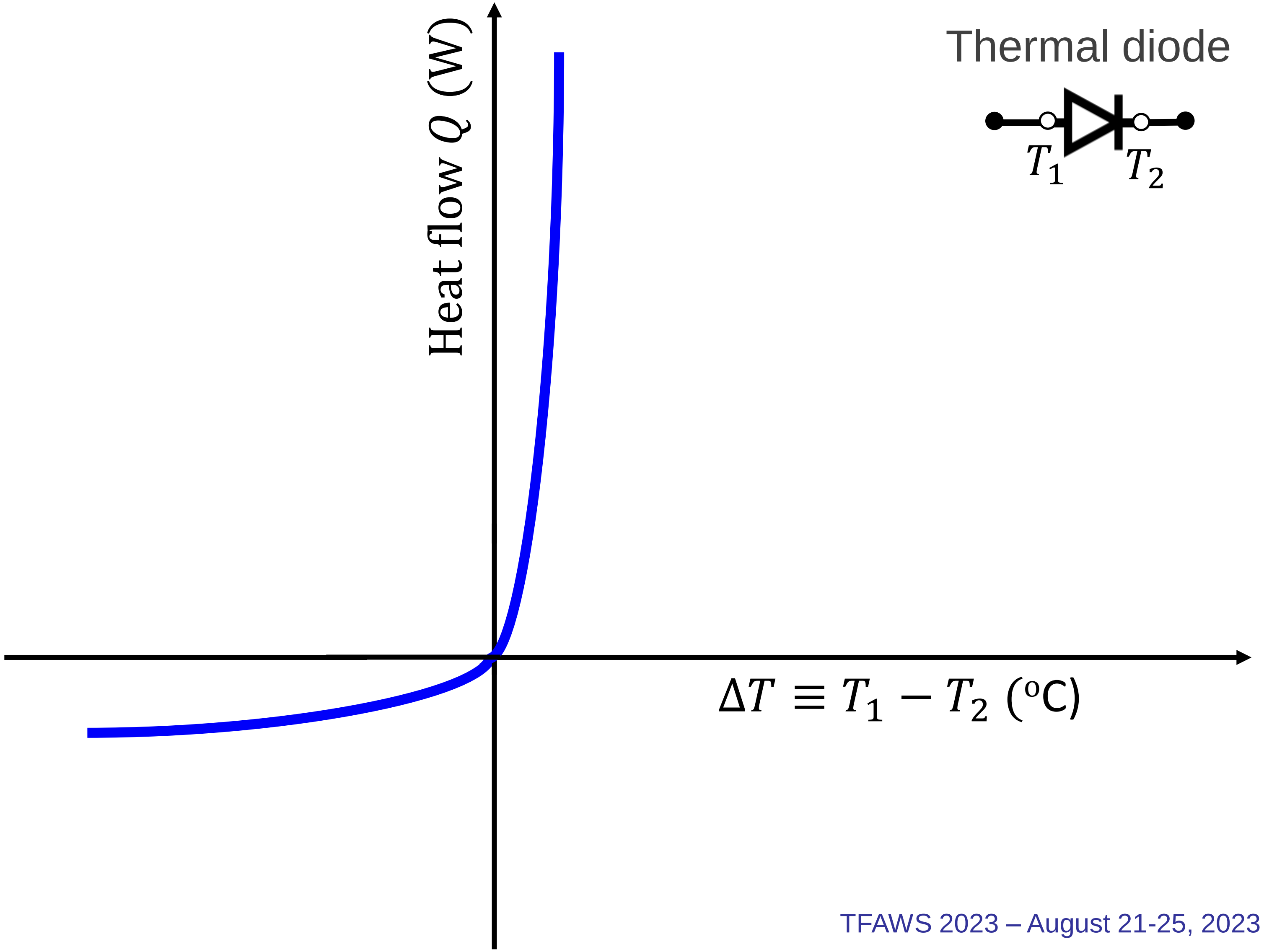


- Gravitational orientation of the regulator does not have a significant effect on the thermal conductance
- Gravity is only about 10% of the gravitational forces in magnitude
- TIM is important to reduce contact resistance in vacuum
- Air environment significantly enhance the off state thermal conductance

A few option of variable insulation are available

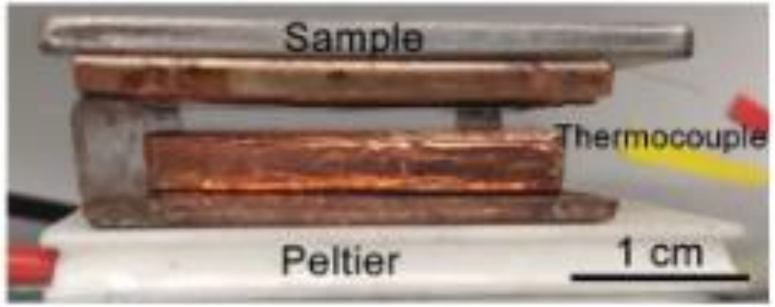


A few option of variable insulation are available



Thermal diode

Not discussed in this presentation



Zhu, Q., Zdrojewski, K., Castelli, L., and Wehmeyer, G. (2022). Oscillating Gadolinium Thermal Diode Using Temperature-Dependent Magnetic Forces. Adv Funct Mater 32, 2206733. 10.1002/adfm.202206733.