N A M e

GDR NAnoMaterials for Energy applications

ELABORATION
MESURES METROLOGIE
SIMULATIONS THEORIE
APPLICATIONS

GDR NAME

Plenary meeting: May 19-21, 2021

Workshop 4: Thermal Management

May 20th 2021

Participants: Younès Ezzahri, Jean-François Robillard, Philippe Ben-Abdallah, Jérémie Drévillon, Nicolas Horny, Karl Joulain, Jérémie Maire, Stéphane Monfray, Elyes Nefzaoui, Stéphane Pailhès and Roberto Simola

NAMe

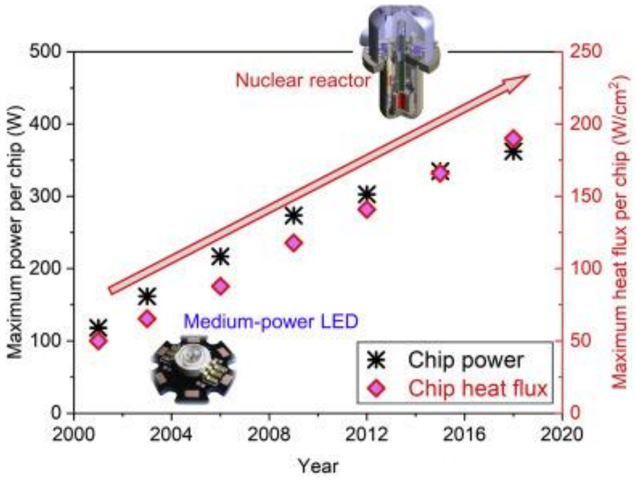
GDR NAnoMaterials for Energy applications

Outline

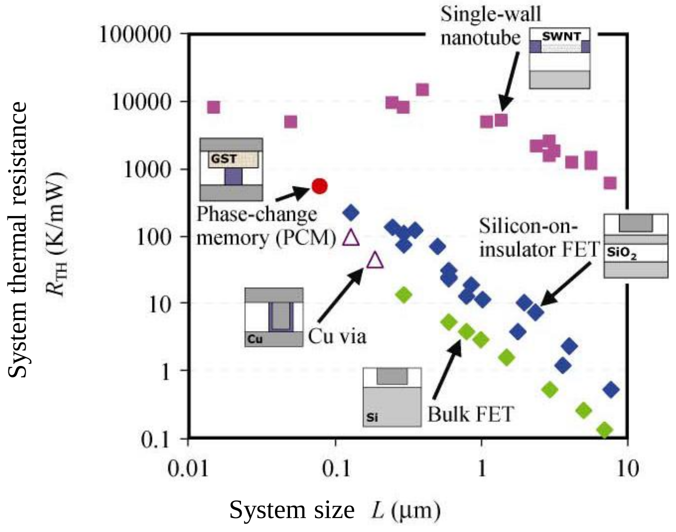
- **Overview**
  - Scaling, power, trends, 3D integration, steady-state / transient
- **Thermal management for Integrated Circuits (IC)**
  - Relevant parameters
    - Thermal conductivity
    - Thermal interface resistance
  - Techniques
    - Passive: Thermal interface materials
  - Applications
    - Phase Change Materials devices
    - Optical components
  - Challenges and perspectives
- **Radiative cooling and heating**
  - Principles
  - Applications
    - Daytime radiative cooling
    - Nighttime radiative cooling
    - Radiative condensers (black silicon)
  - Challenges and perspectives
- **Thermotronics**
  - Overview
    - Historic breakthroughs in electronics
    - A variety of thermal analogues to the electrical components
    - Analogies between linear electrical and thermal components
  - Thermal rectifiers and thermal diodes
  - Thermal regulators and thermal switches
  - Thermal transistors
  - Thermal logical gates and memories
  - Thermal memristors
  - Active control of heat flux
  - How about the quantum regime?
  - Challenges and perspectives

Overview

Orders of magnitude



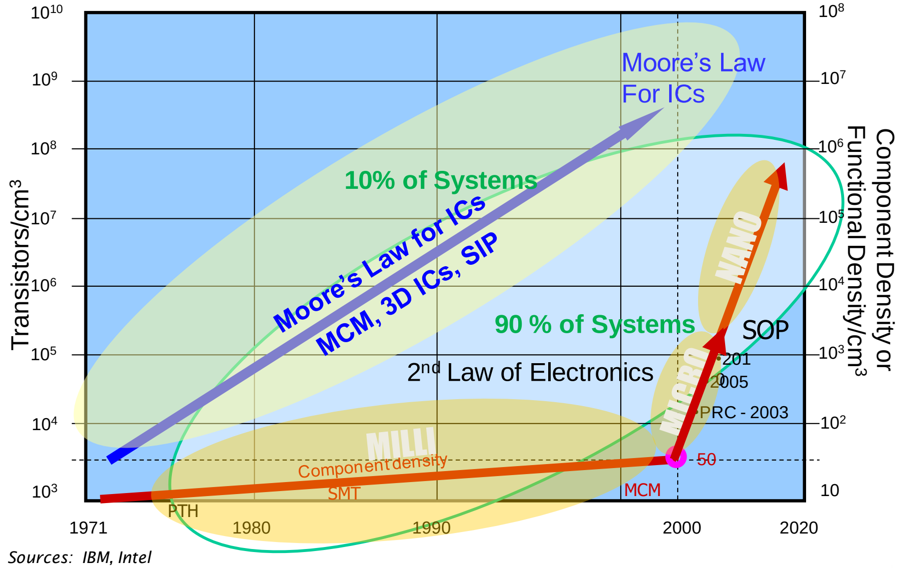
X.-H. Yang and J. Liu, in Advances in Heat Transfer, ***50****, 187–300 (2018)*

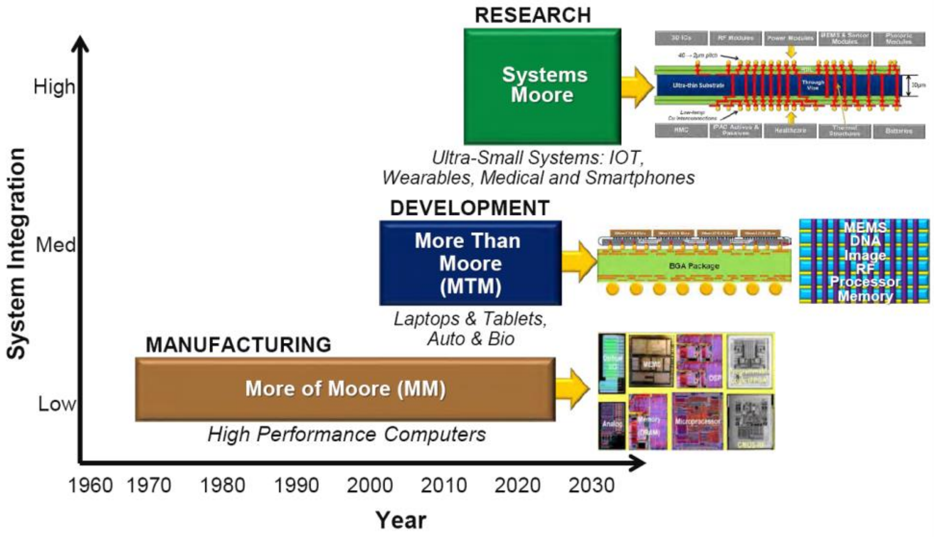


E. Pop, Nano Res (2010) ***3****: 147–169*

Trends

From “more Moore” to “system Moore”

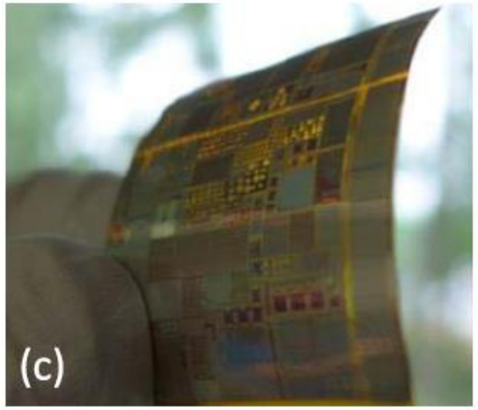


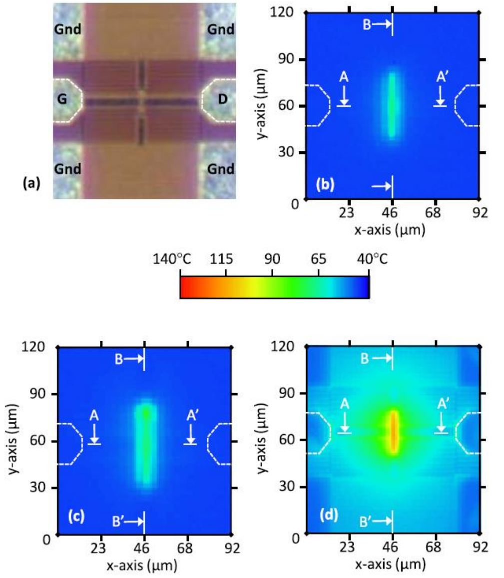


R. Tummala, System-On-Package (SOP), Mc Graw-Hill 2008

Trends

Flexible electronics





J. Philippe et al. , Journal of the Electron Devices Society, ***7****, 973 (2019)*

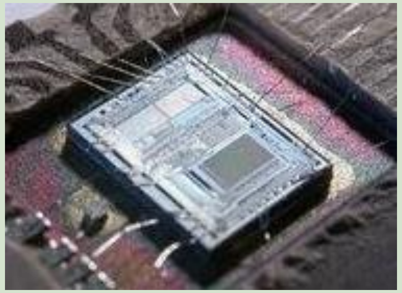
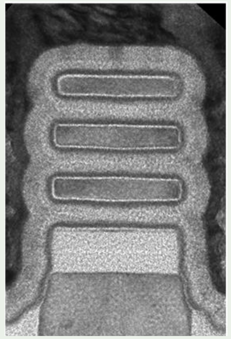
NAMe

GDR NAnoMaterials for Energy applications

Thermal Management for IC

J.-F. Robillard

Relevant scales

2 m – 10 cm	System Device		Forced convection-Fans Liquid cooling Peltier Cooling **Thermal Interface Materials**
2 cm – 0.5 mm	Integrated Circuit		Heat sinks **Thermal Interface Materials** **Integrated Peltier Cooling ?** Thermal floor planning
100 µm – 2 nm	Component		Through Silicon Vias Routing strategies Quality of interfaces **-> Thermal Interface Resistance** Knowledge of materials **-> Thermal Conductivity**

The 2 nm transistor in nanosheet structure. (Credit: IBM) (2021)

Relevant parameters

At component scale, knowledge of
Thermal conductivity (TC)
Thermal boundary resistance (TBR)
becomes critical for IC design…

Types of management

Active	Passive
Peltier	Heat sinks
Forced convection	Thermal floor planning
	Vias-Routing

Objectives of management

Component reliability
Heat spreading (data, com, memories…)

Component performance/efficiency
Noise reduction (imagers, detectors)

Component operation
« Heat as a resource »
Non-volatile memories (PCM)
Thermo-optical modulation

Thermal Management for IC

Thermal interface resistance / conductance

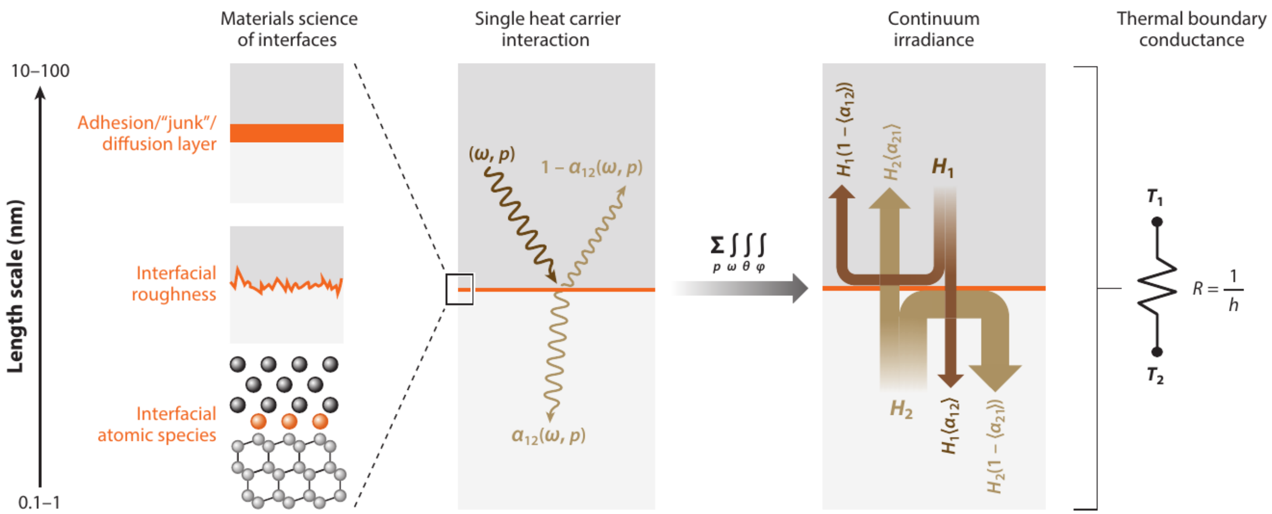
$$h_k = 1/R_k = \frac{\varphi}{\Delta T} [W \cdot m^{-2} \cdot K^{-1}]$$

Kapitza conductance technically refers to the conductance across an infinitesimally thin (atomically perfect and abrupt) surface or interface.

However, **Thermal Boundary Conductance** can refer to a more general, spatially broad interfacial region (ex :phonon scattering a few atomic layers away from the actual "interface" can dictate the reported h_k).

Main factors h_k for solid/solid

- Quality of the interface (roughness, oxyde)
- Strength of interatomic interactions at the interface
- Dispersion and density of states (DOS) for energy carriers
- Temperature
- Pressure



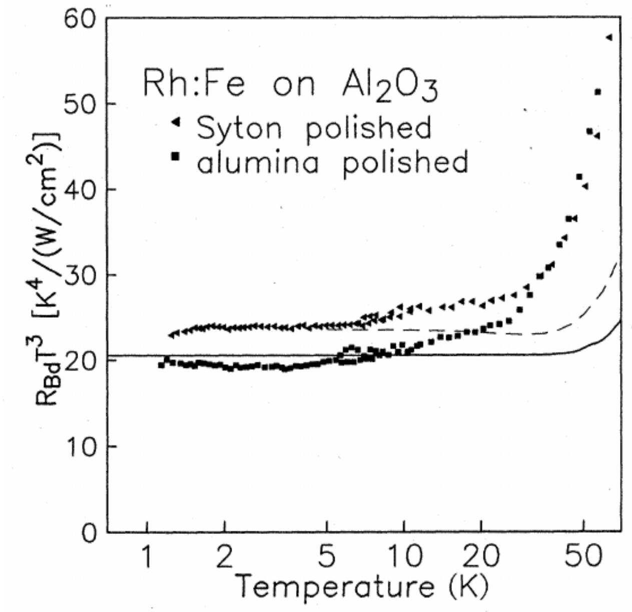
- *Hopkins, P. E. (2013). "Thermal transport across solid interfaces with nanoscale imperfections: effects of roughness, disorder, dislocations, and bonding on thermal boundary conductance." International Scholarly Research Notices, 2013.*
- *Monachon, C. et al. , Annual Review of Materials Research,* ***46****, 433-463.*
- *Maïté Blanck et al, J. Appl. Phys.* ***125****, 095302 (2019)*
- *A. Giri, and P. E. Hopkins, Advanced Functional Materials,* ***30****(8), 1903857 (2020)*

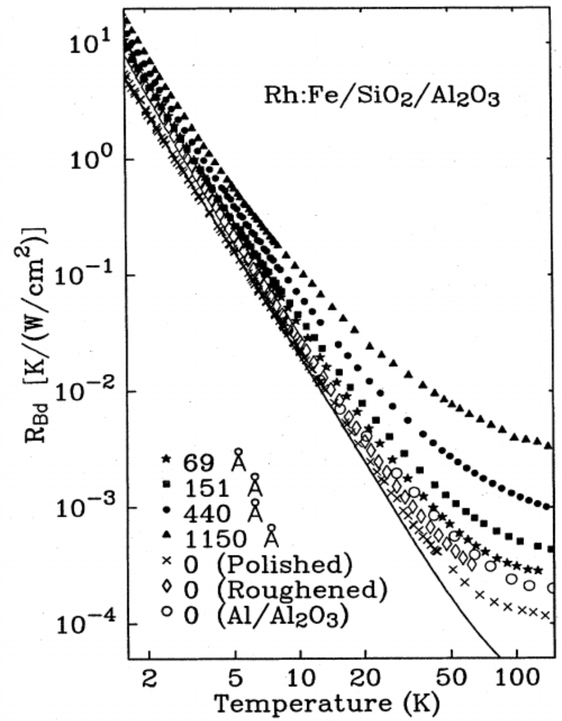
Thermal Management for IC

Thermal interface resistance / conductance

T^3 dependence at low T

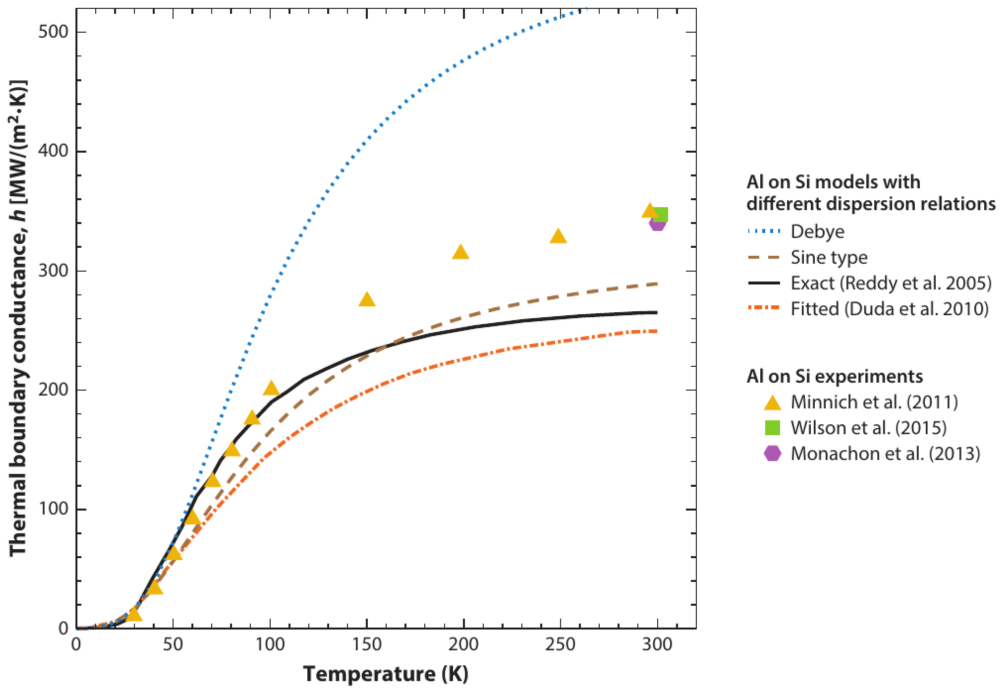
« Thermal resistance at interfaces »
E. T. Swartz and R. O. Pohl, Appl. Phys. Lett. ***51****, 2200 (1987)*
« Thermal boundary resistance »
E. T. Swartz and R. O. Pohl, Rev. Mod. Phys. ***61****, 605 (1989)*





Diffuse Mismatch model

C. Monachon, et al. ,
Annual Review of Materials Research, ***46****, 433-463.*

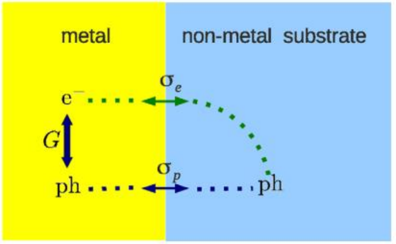


Thermal Management for IC

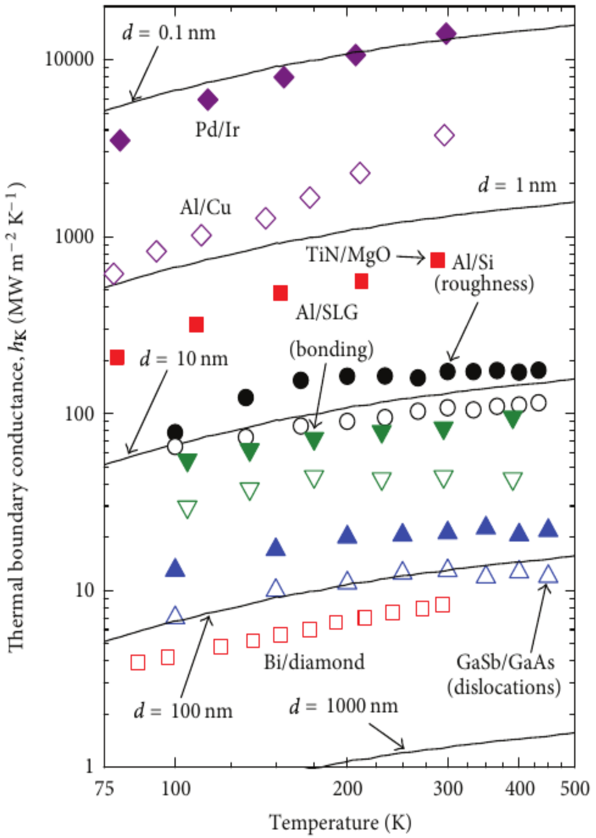
N. Horny

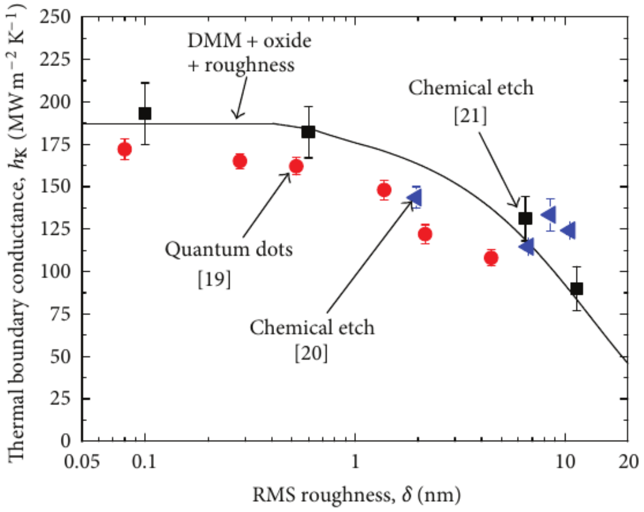
Thermal interface resistance / conductance

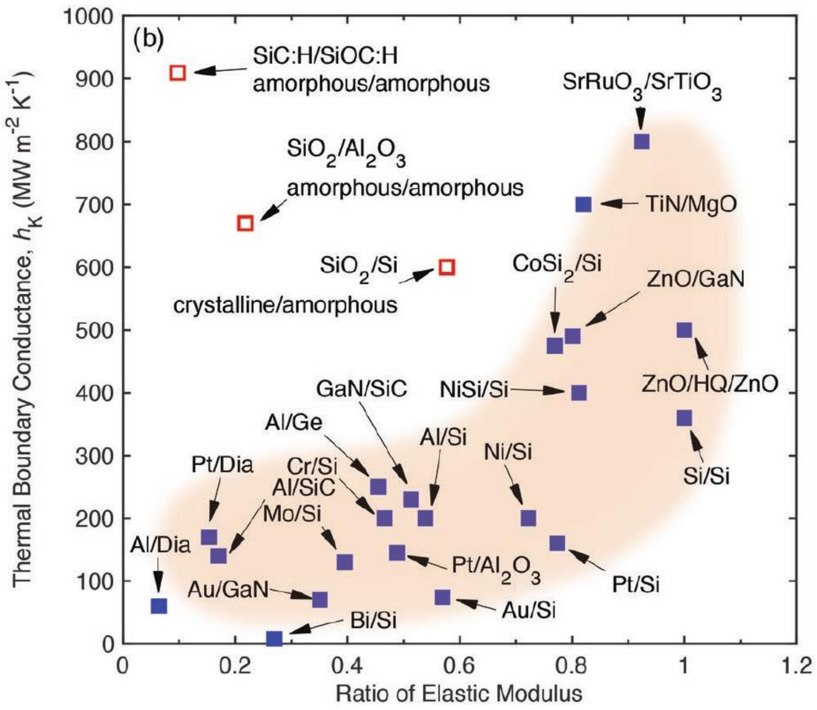
- metal-metal : TBC is dominated by electron transport
- metal-nonmetal : TBC is dominated by phonon transport
- Effect of roughness
- Effects of Lattice Dislocations



J Lombard, F Detcheverry and S Merabia, *J. Phys.: Condens. Matter* *27* (2015).







A. Giri, and P. E. Hopkins, Advanced Functional Materials, ***30****(8), 1903857 (2020)*

Hopkins, P. E. (2013). "Thermal transport across solid interfaces with nanoscale imperfections: effects of roughness, disorder, dislocations, and bonding on thermal boundary conductance." International Scholarly Research Notices, 2013.

NAME

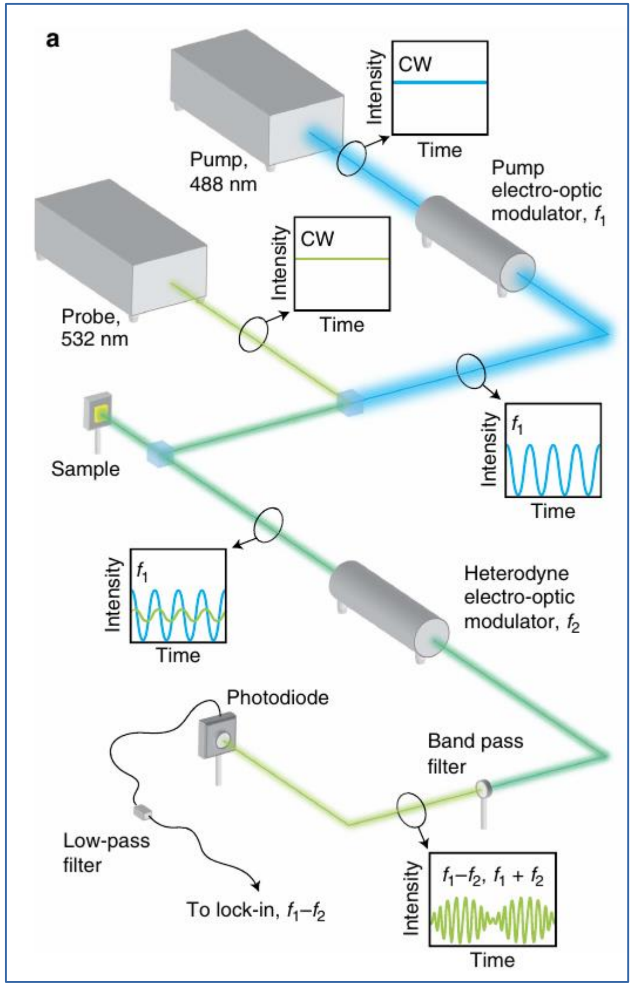
GDR NAnoMaterials for Energy applications

Thermal Management for IC

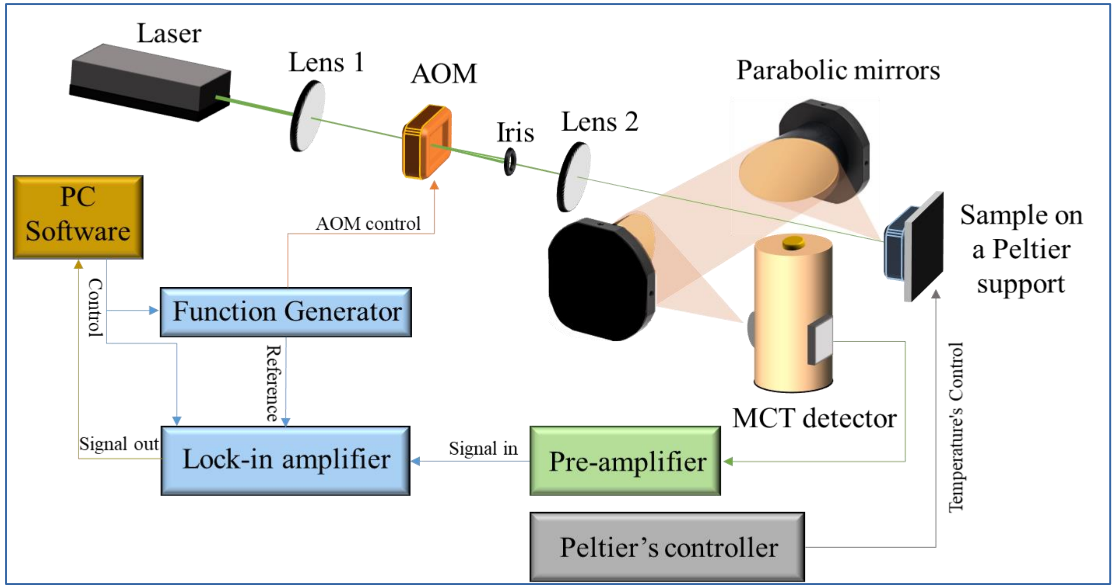
N. Horny

- **Thermal interface resistance / conductance** **Multiscale thermal characterization techniques**

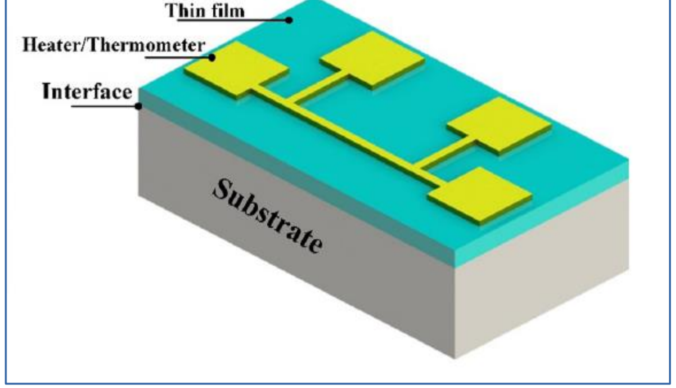
Time or frequency domain ThermoReflectance



Time or frequency domain Photothermal Radiometry



3ω method



N A M e

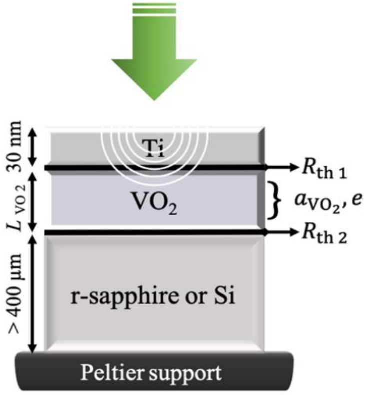
GDR NAnoMaterials for Energy applications

Thermal Management for IC

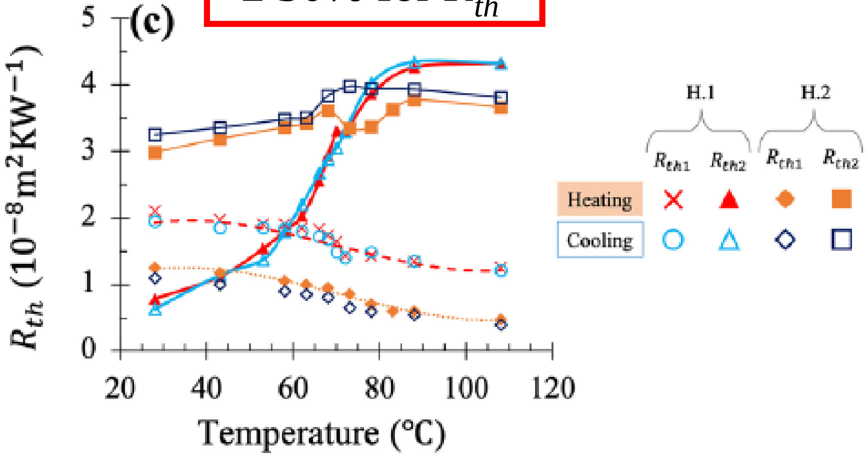
N. Horny

Applications ● Phase Change Materials devices

Thermophysical characterisation of VO_2 thin films hysteresis

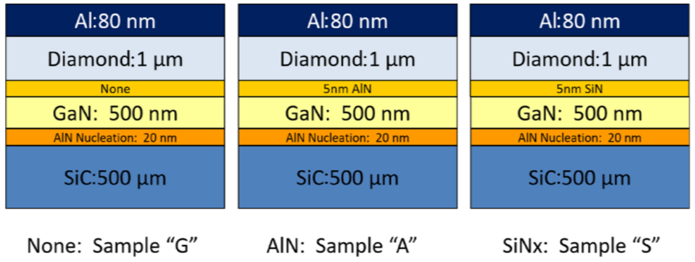


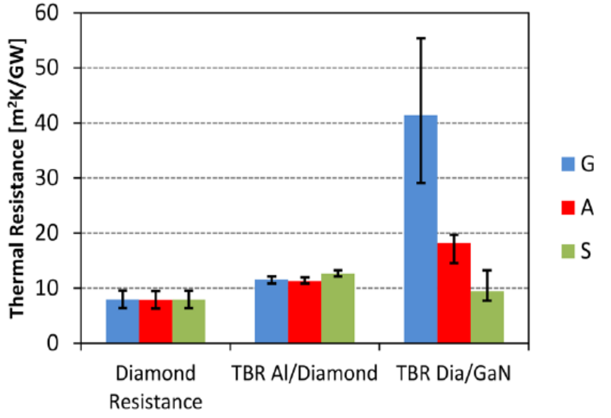
± 30% for R_{th}



G. Hamaoui, et al.
Scientific reports, **9**, *1-10 (2019).*

Low Thermal Boundary Resistance Interfaces for GaN-on-Diamond Devices





Yates et al., ACS Appl. Mater. Interfaces 2018, 10, 24302−24309 (2018)

Electronic contribution in heat transfer at metal-semiconductor and metal silicide-semiconductor interfaces

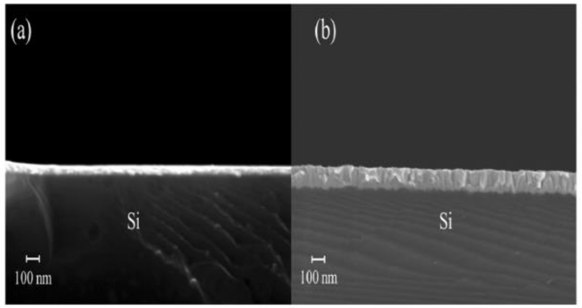
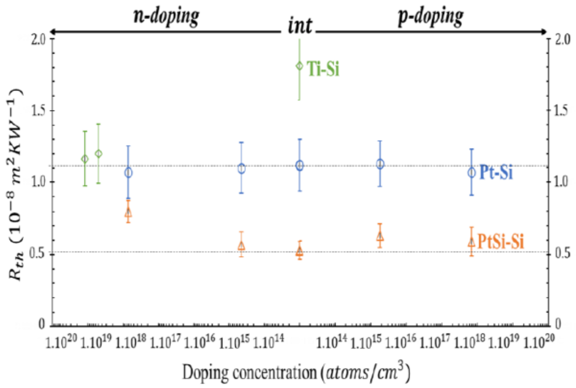


Figure 3. Example of a SEM images for the S3 samples: (a) unannealed Pt-Si and (b) annealed PtSi-Si samples.



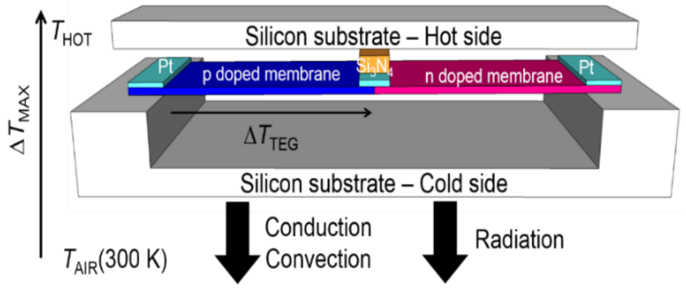
G. Hamaoui et al. Scientific reports, **8**, *1-9 (2018).*

Thermal Management for IC

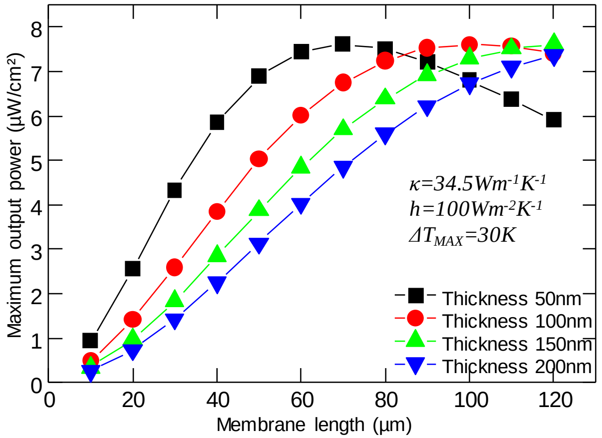
J.-F. Robillard

Applications — Thermoelectric Energy harvesting

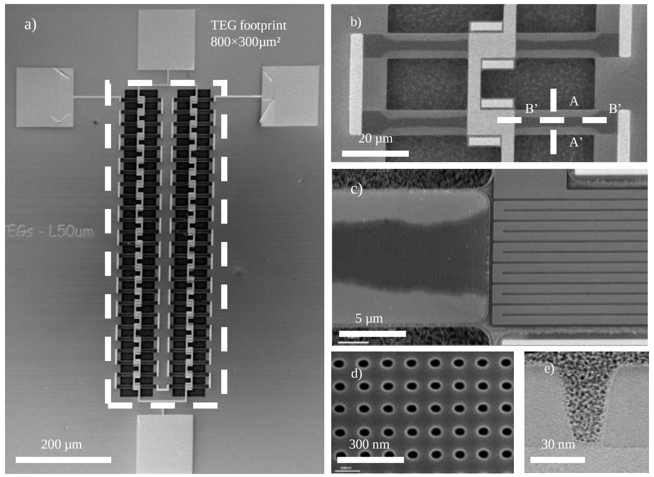
Attempts to integrate membrane-like or NW TE Converters lead to new thermal management issues.
Mainly related to the vertical to horizontal heat flux redirection
And air exchange.



Device optimization

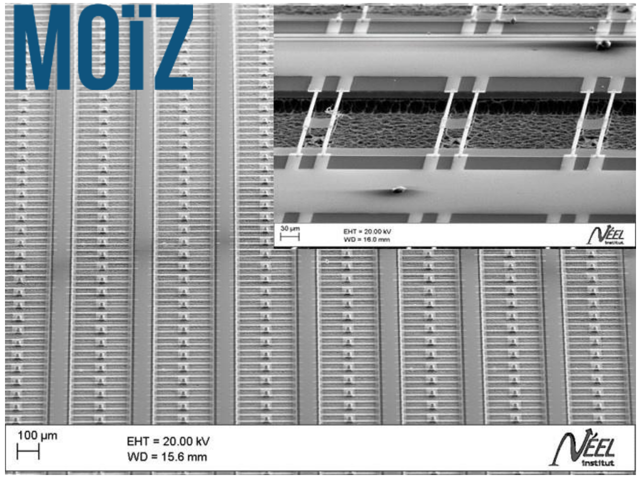


c-Si Membranes



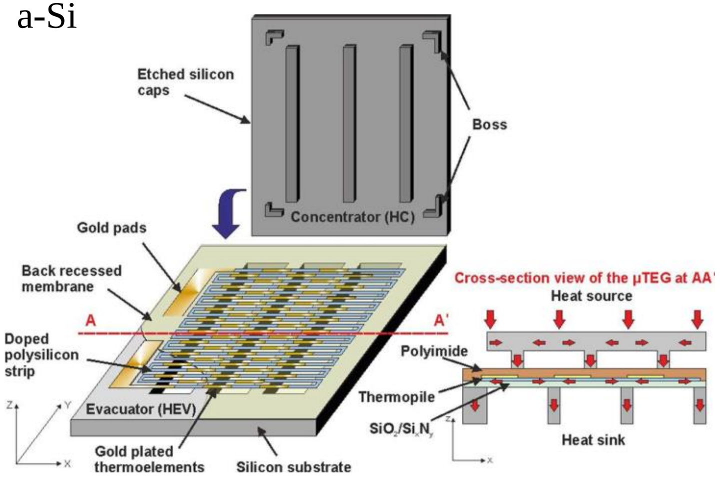
*M. Haras et al. IEEE Electron Device Letters, **37**, 1358 (2016)*
T. M. Bah et al. (in prep.)

Bi2Te3 — Air flow



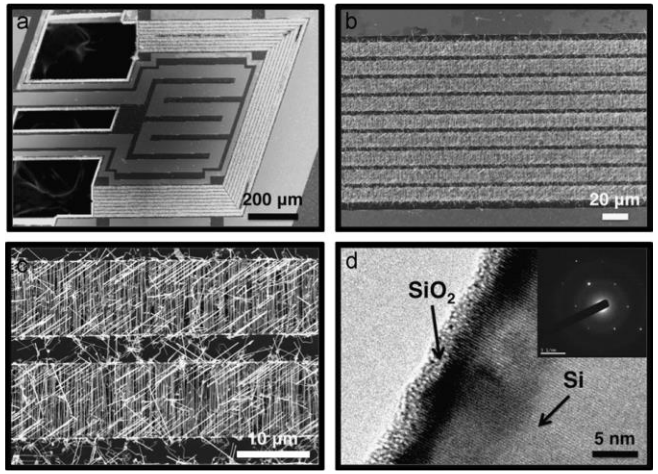
*D. Tainoff etal . Nano Energy **57** 804–810 (2019)*

a-Si



*K. Ziouche et al. Journal Of Microelectromechanical Systems, **26**, 45 (2017)*

c-Si NW



*D. Davilà et al. Nano Energy **1,** 812 (2012)*

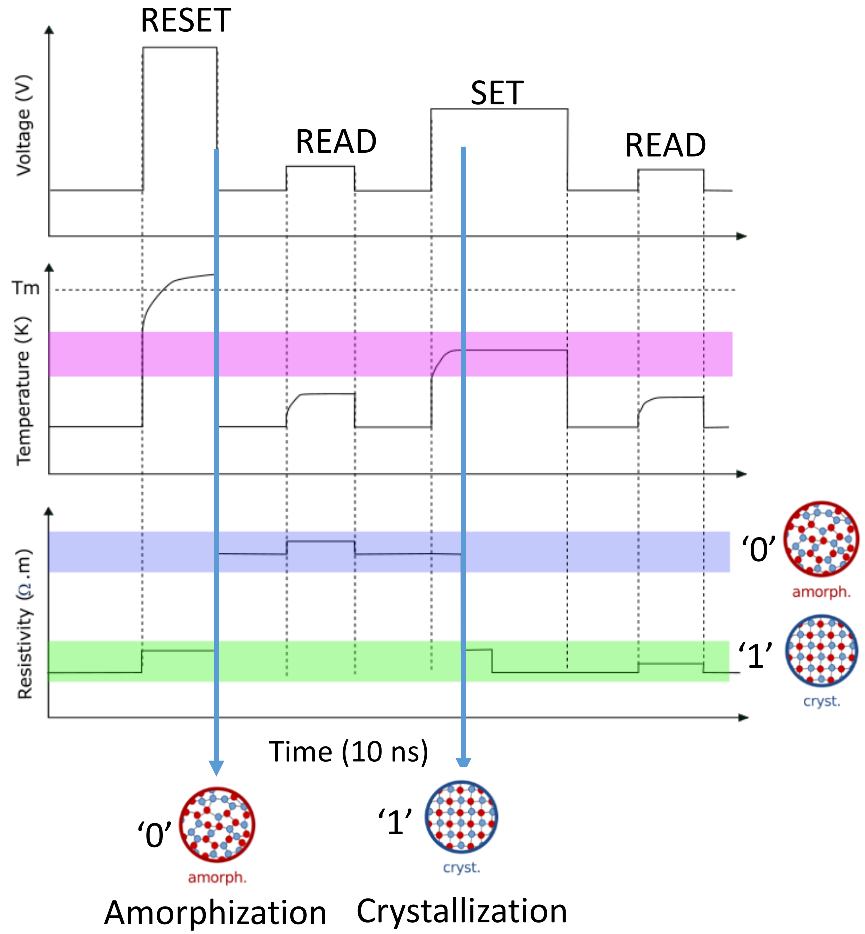
Thermal Management for IC

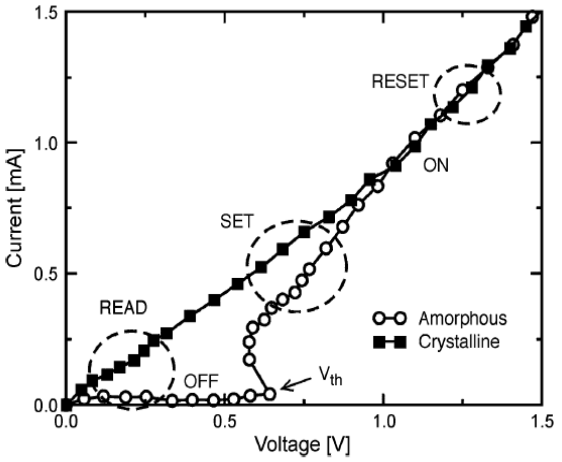
J.-F. Robillard
R. Simola

GDR NAnoMaterials for Energy applications

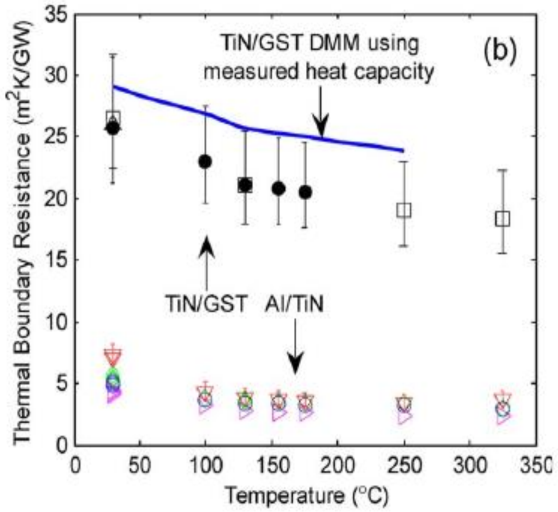
Applications Phase Change Materials devices

- Transition between amorphous and crystalline phase
- Phase transition – current induced Joule heating
- Information stored in the resistance of the alloy

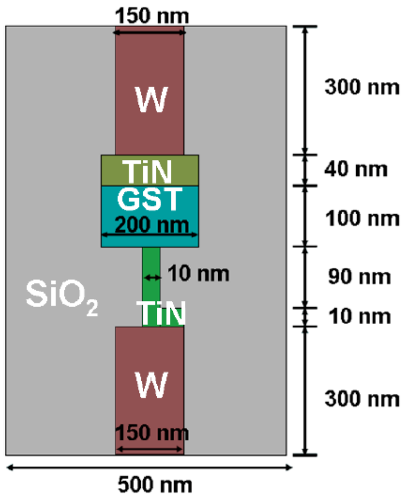


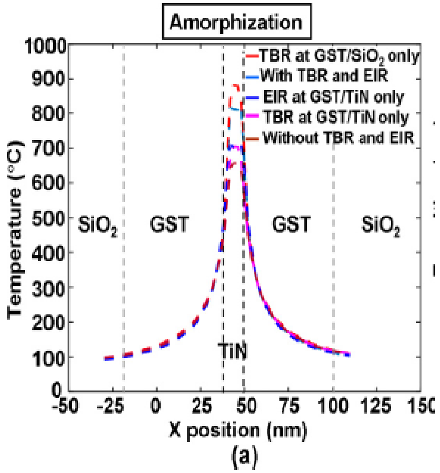


A. Pirovano et al IEEE Trans. Electron Devices, ***51****, 452 (2004).*



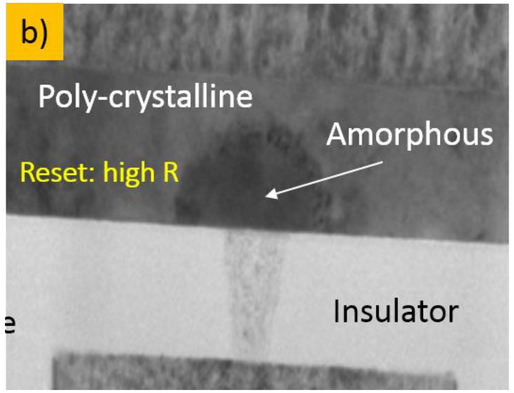
John P. Reifenberg, et al. IEEE Electron Device Letters, ***31****, NO. 1, (2010)*





J. Wen et al IEEE Transactions on Electron Devices, ***67*** *(2020)*

Typical thicknesses of µelec layers have a thermal resistance equivalent to TBR. TBR can be a major contribution to the total thermal resistance.



IBM Research / Memory Technologies

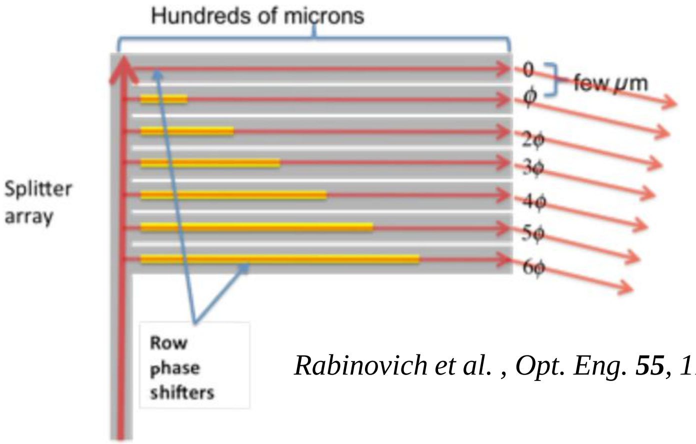
Thermal Management for IC

J.-F. Robillard
S. Monfray

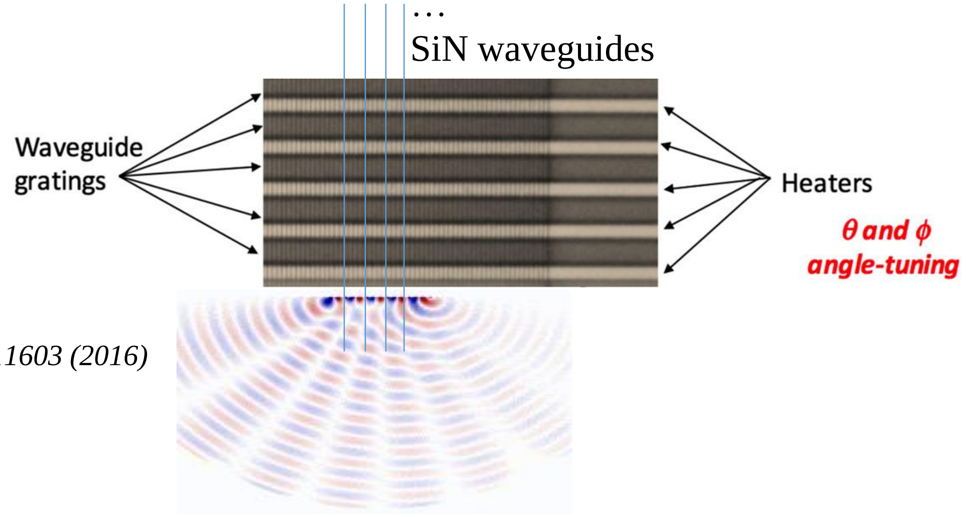
Applications

LIDAR: Beam steering with thermo-optical waveguides

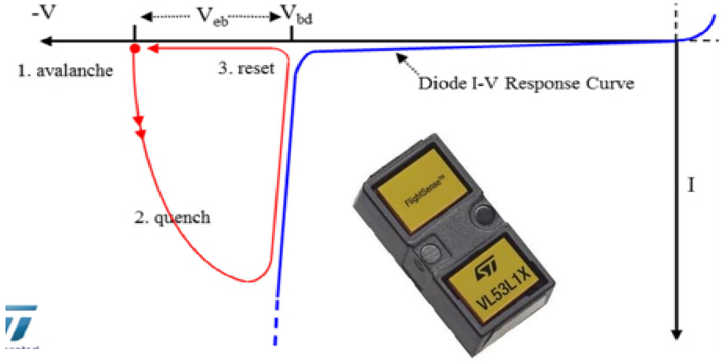
- For IR (905 nm)
- SiN waveguides
- Thermo-optical modulation
- Challenge=go to high frequencies (10-50kHz)
- Need for thermal optimization



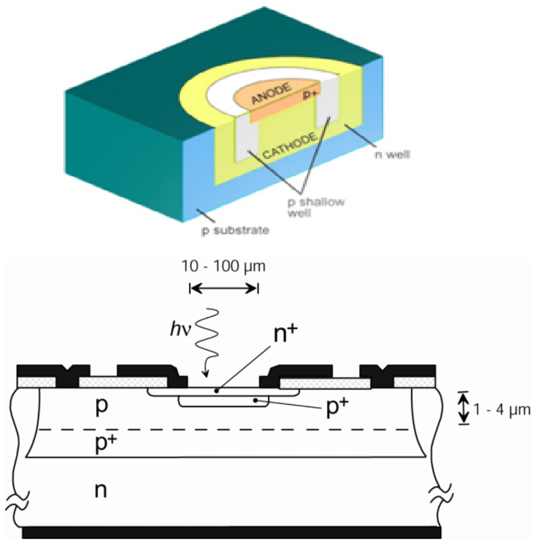
Rabinovich et al. , Opt. Eng. ***55****, 111603 (2016)*

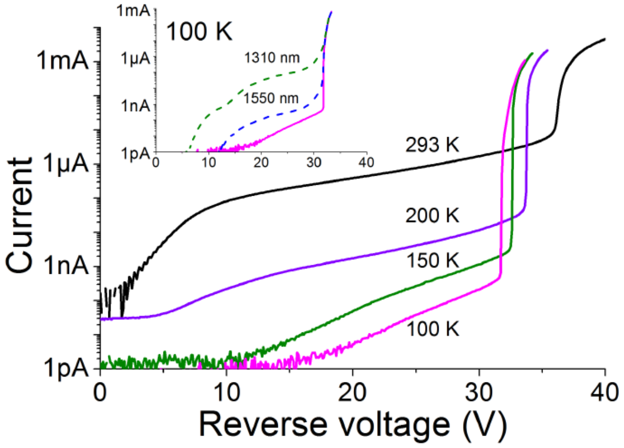


Detection and imaging : Single Photon Avalanche Diodes



Si 905 nm
Ge 1300 nm





R. E. Warbuton et al. , Trans. on Electron devices, ***60****, 3807 (2013)*

- Dark Count Rate
- Noise Eq. Power

Can be highly improved through local cooling

NAMe GDR NAnoMaterials for Energy applications

Thermal Management for IC

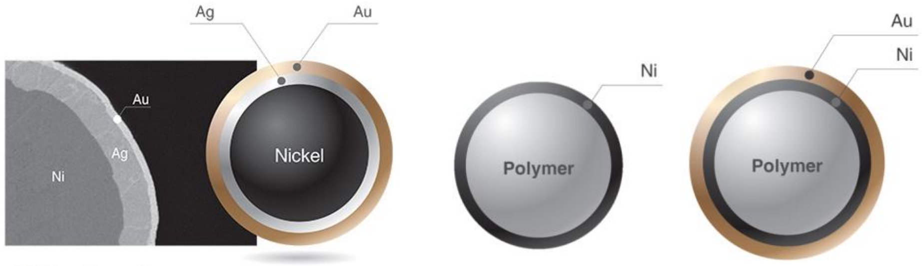
Techniques ● Passive: Thermal interface materials

TIMs for 5G/AI/Semiconductors

Electrically conductive adhesives - alternative to solders (electronic packaging)

Elastomer socket powder – semiconductor testing

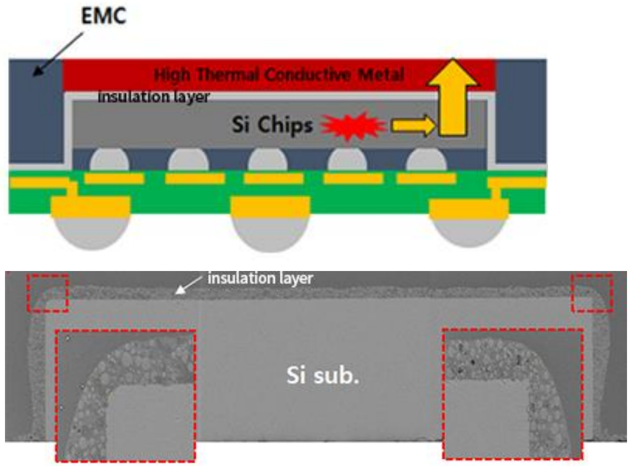
Conductive powder - touch screen panels

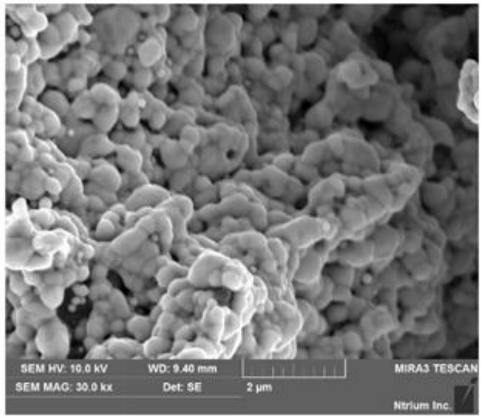


»Ni + Ag + Au

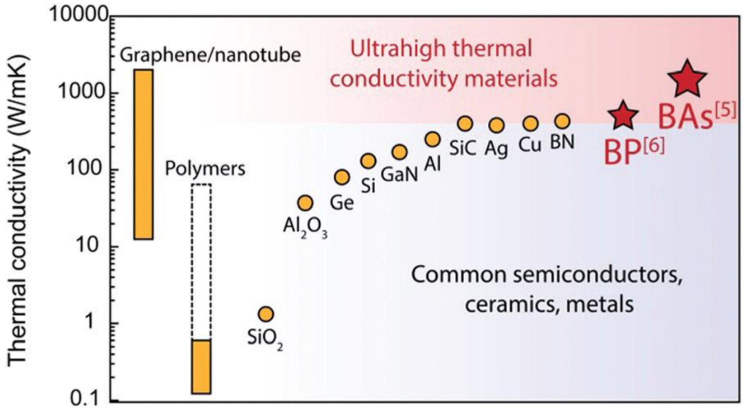
High thermal ceramic paste for spray – electrical insulator / spray

High Thermal Ag Sintering Paste – high thermal conductivity





Ultrahigh phonon conductivity materials

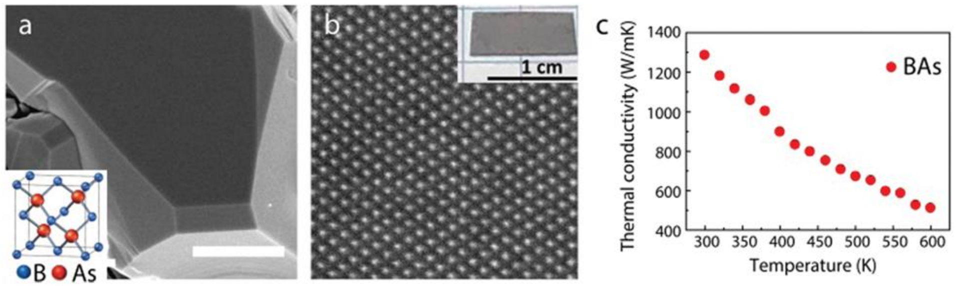


Primarily Synthetic diamond, BN, SiC, Ag, Al, and Cu

Coefficient of thermal expansion should match the heat source

acoustic phonon bunching
large acoustic-optical gaps

e.g., BP, BAs



GDR NAnoMaterials for Energy applications

Thermal Management for IC

J. Maire

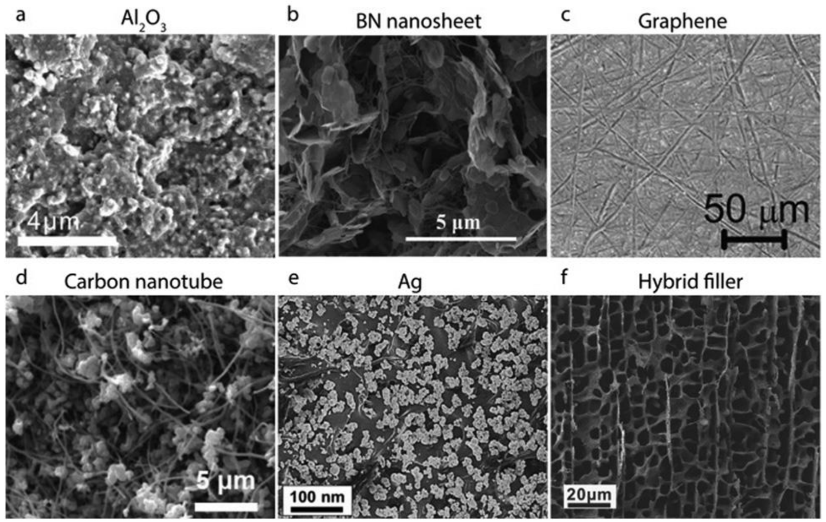
Techniques

Passive: Thermal interface materials

2D Materials for thermal management

Fillers for Polymer-Based TIMs

- Ultrahigh thermal conductivity of graphene (semi-metal)
- high conductivity of h-BN (insulator)

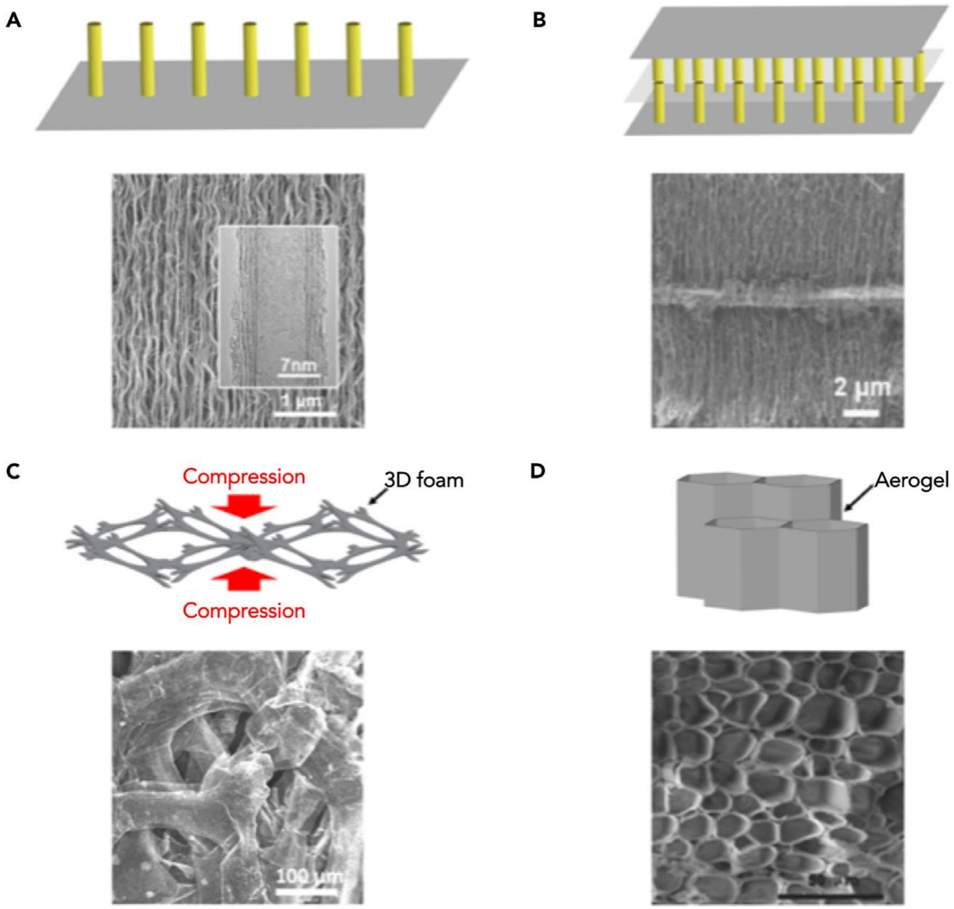


high κ with minimized filler loading

- graphene flakes with Ag particles
- h-BN flakes with SiC nanowires
- Ag flakes with CNTs

Direct Use for Thermal Management

2D Materials and 3D assemblies



- 3D-Interconnected Graphene and H-BN Macroforms
  Graphene and h-BN Thin Films for Heat Spreaders
- Graphene Fibers for Thermal Management

Thermal Management for IC

Challenges and perspectives

Challenges

- Heterogeneity : increased functionnal density leads to more materials and complex structures
- Mechanical flexibility : can lead to extra thermal resistance due to transfer bonding
- Metrology : TBR in realistic devices stacks
- Modeling : Taking into account non-Fourier conduction in complex structures
- Introduction of nanostructures in devices (NW, membranes) : Leads to new challenges in thermal design
- Paradoxically, high thermal conductivity nanostructures (carbon NW, graphene) can lead to degraded thermal management

Perspectives

- Very high phonon conductivity materials
- Integrated Peltier cooling
- « Heat as a resource » devices (PCRam, PC Switches)

NAMe
GDR NAnoMaterials for Energy applications

Atelier 4

Thermal Management

About this workshop:

- Very rich contents within the GDR and beyond
- We realized that some topics are not covered at all -> Please join !
- This is quite transversal topic and related to other Workshops.

Difficulties:

- Terminology and scope definition

The full presentation,
including Radiative Cooling and Thermotronics,
will be presented in next session, October.

Thanks to all contributors :

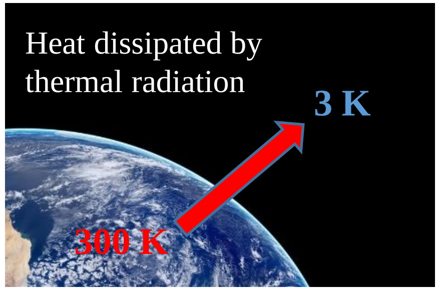
Younès Ezzahri
Jean-François Robillard
Philippe Ben-Abdallah
Jérémie Drévillon
Nicolas Horny
Karl Joulain
Jérémie Maire
Stéphane Monfray
Elyes Nefzaoui
Stéphane Pailhès
Roberto Simola

Radiative cooling

J. Drévillon

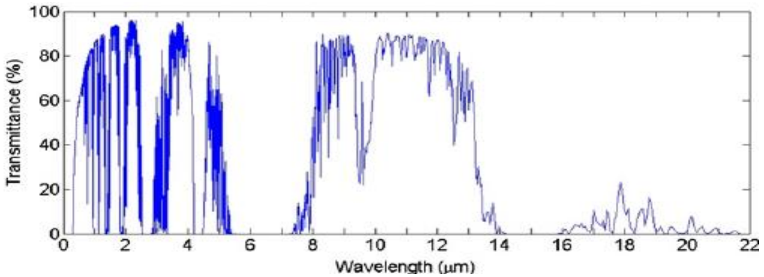
Principles

- Using the cold darkness of space

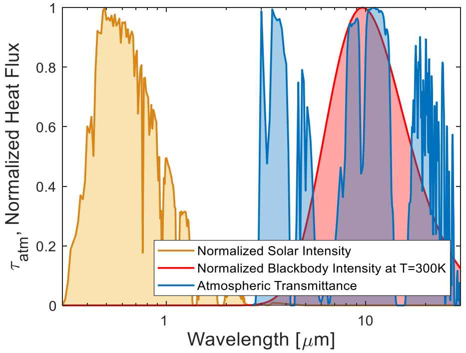


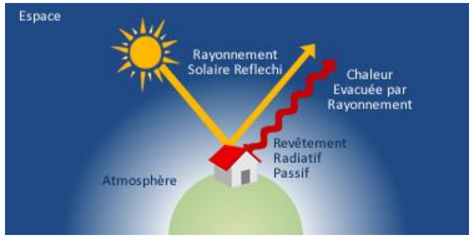
- Natural nocturnal radiative cooling

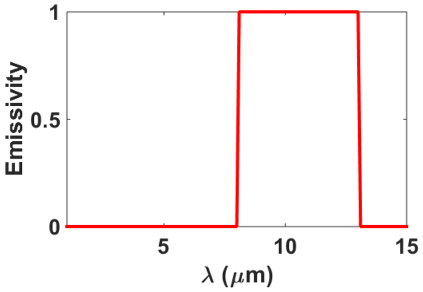
- Atmospheric transmittance



Passive daytime radiative cooling

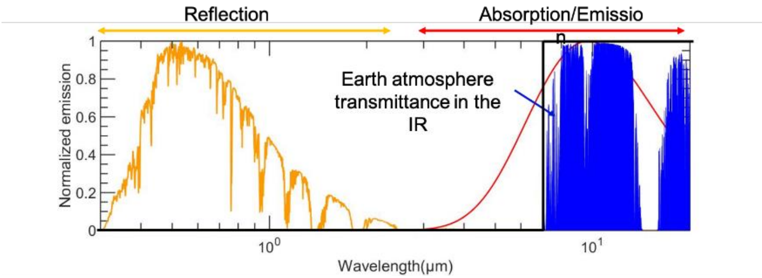


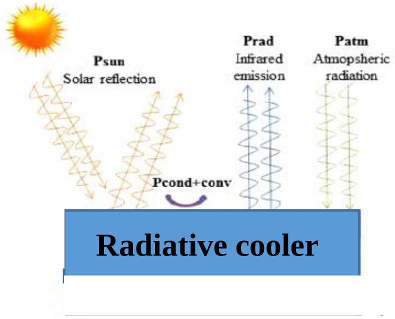




- High emission in the [8, 13]μm interval: *Atmosphere transparency window*
- High reflection in the rest of the spectrum in order to avoid absorption of the solar radiation.

Requires spectral control of the surface emission/reflection.





Radiative cooling power

$$P_{cool}(T) = P_{rad}(T) - P_{atm}(T_{amb}) - P_{sun} - P_{cond+conv}$$

- $P_{rad}(T)$: Power emitted by the structure
- $P_{atm}(T_{amb})$: Power absorbed due to incident atmospheric radiation
- P_{sun}: Absorbed incoming power from the sun
- $P_{cond+conv}$: Exchanged power due to conduction and convection

$$P_{rad}(T) = A\int d\Omega \cos\theta \int_0^{\infty} d\lambda I_{BB}(T,\lambda)\varepsilon(\lambda,\theta)$$

$$P_{atm}(T_{amb}) = A\int d\Omega \cos\theta \int_0^{\infty} d\lambda\, I_{BB}(T_{amb},\lambda)\varepsilon(\lambda,\theta)\varepsilon_{atm}(\lambda,\theta)$$

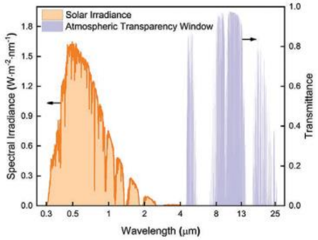
$$P_{sun} = A\int_0^{\infty} d\lambda \varepsilon(\lambda,0) I_{AM\,sw1.5}(\lambda) + A\int d\Omega \cos\theta \int_0^{\infty} d\lambda I_{solar-diffuse}(\lambda)\varepsilon(\lambda,\theta)$$

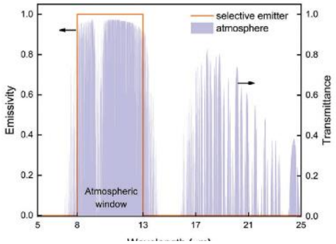
$$P_{cond+conv}(T,T_{amb}) = Ah_c(T_{amb} - T)$$

Radiative cooling

Different approaches

- Nanophotonic approach
- Scalable approach : paint / polymer films





- How to optimize the emission in the transparency spectrum of the atmosphere?
- How to minimize solar absorption?

Nanophotonic approach: thin films stack

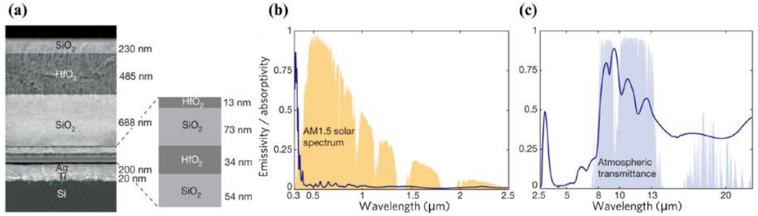
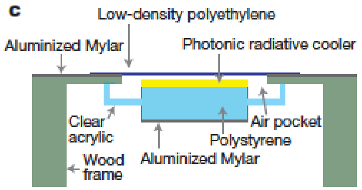
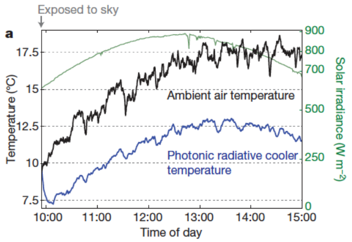
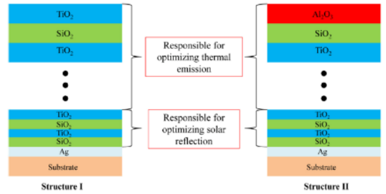


Fig. 13. Scanning electron microscope and spectral characterizations of a photonic radiator (multilayer film) reported in Ref. [13].



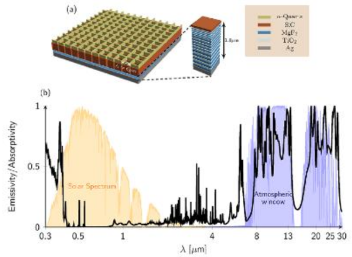


AP. Raman et al., *Nature*, **515**, 540 (2014).



R. Family and M. P. Mengüç, *Proc Environ Sci*, **38**, 752 (2017).

Metamaterials with patterned surface



E. Rephaeli et al., *Nano Lett*, **13**, 1457 (2013).

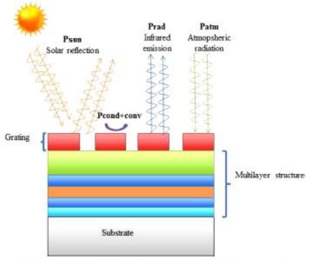
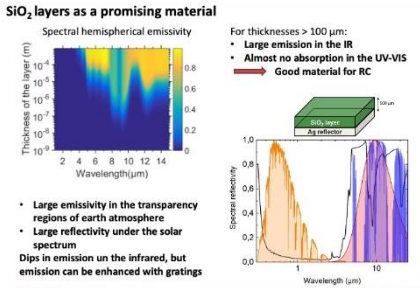


Fig. 1. Schematics of a radiative cooler composed of a multi-layer structure and a grating overhead with the radiative and nonradiative processes taking place.



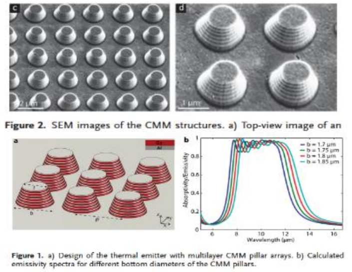
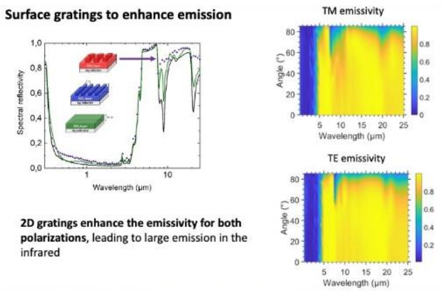


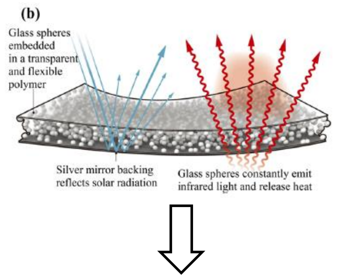
Figure 1. a) Design of the thermal emitter with multilayer CMM pillar arrays. b) Calculated emissivity spectra for different bottom diameters of the CMM pillars.

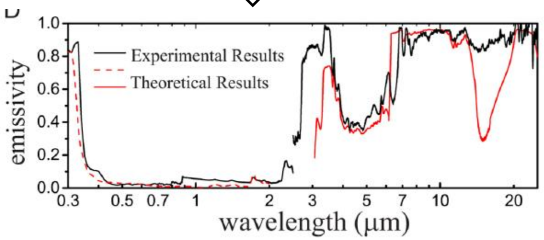
M. M. Hossain et al., *Adv. Opt. Mater*, (2015).

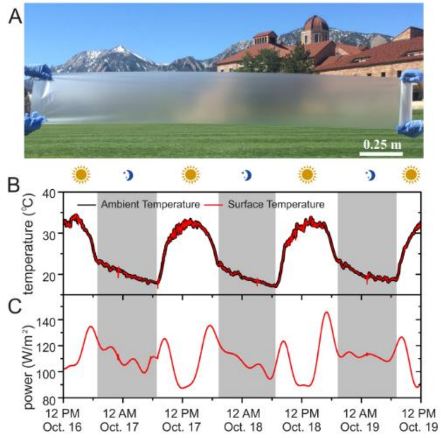


A. Hervé, et al., *JQSRT*, **221**, 155 (2018).

Random polar particle distribution within a polymer







Y. Zhai et al., *Science*, **355**, 1062 (2017).

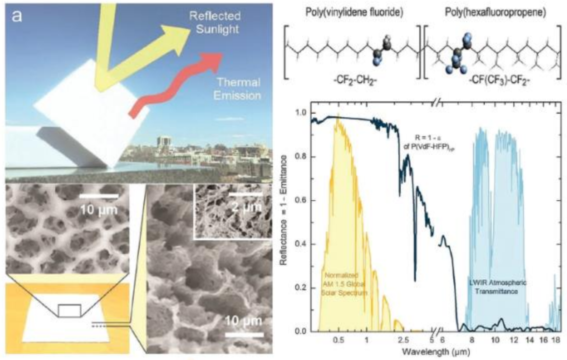
GDR NAnoMaterials for Energy applications

Radiative cooling

J. Drévillon
E. Nefzaoui

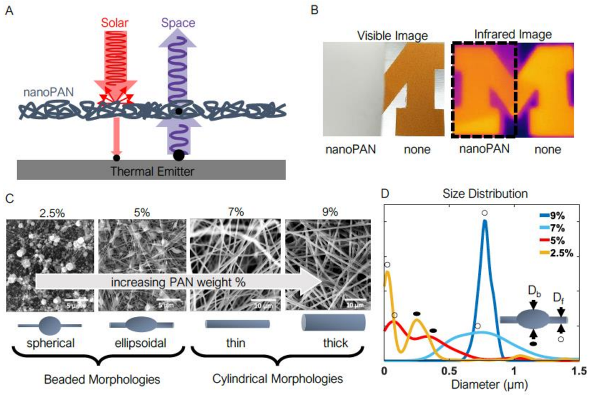
Different approaches

Nano/micro porous polymer

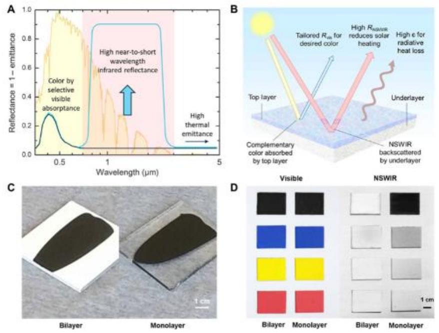


J. Mandal et al., Science ***362****, 6412 (2018).*

Polymer nanofibers



H. Kim e al., ACS Applied Materials & Interfaces, ***12****, 43553 (2020).*



Y. Chen et al., Science Advances, ***6****, 1 (2020).*

SiO_2 nanofibers

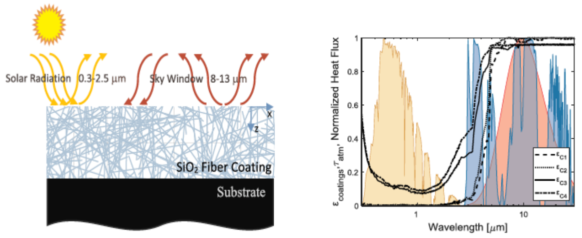
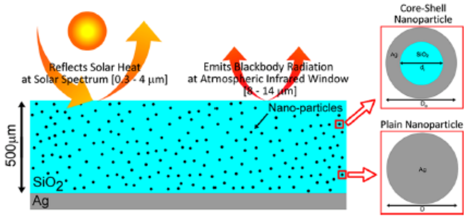


Fig. 2. Schematic of the double layer coating used for radiative cooling.

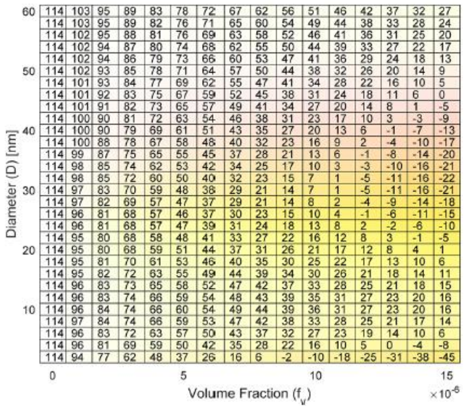
Fig. 14. Spectral emittance of four different coatings at normal incidence from Table 1, spectral solar irradiance, spectral blackbody power and atmospheric transmissivity.

R. Yalçın et al., Solar Energy Materials and Solar Cells, ***206****, 110320 (2020).*

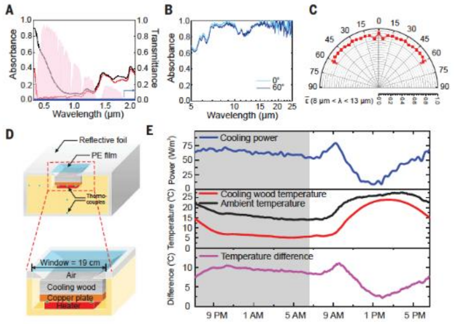
Colored PDRC

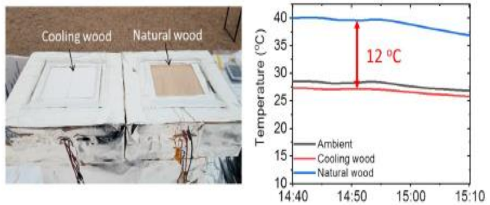


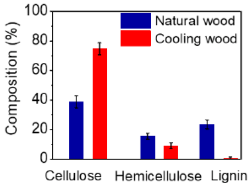
R. Yalçın et al., ACS Photonics, ***7****, 1312 (2020).*



Delignified wood

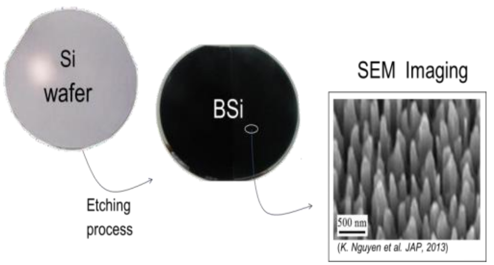


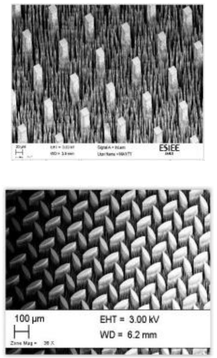


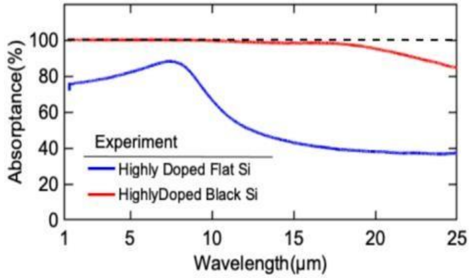


T. Li et al., Science, 364, 6442 (2019).

Black silicon (Bsi)







N A M e

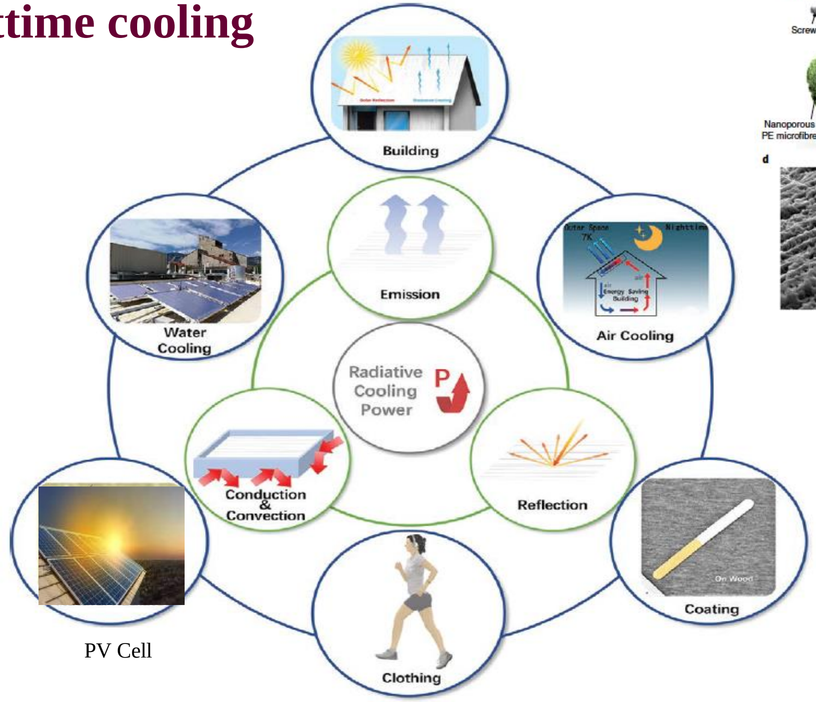
GDR NAnoMaterials for Energy applications

Radiative cooling

J. Drévillon
Y. Ezzahri

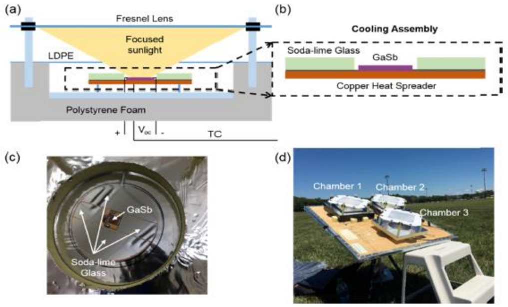
Applications

Multiple potential applications: daytime and nighttime cooling



PV Cell

PV/TPV cooling

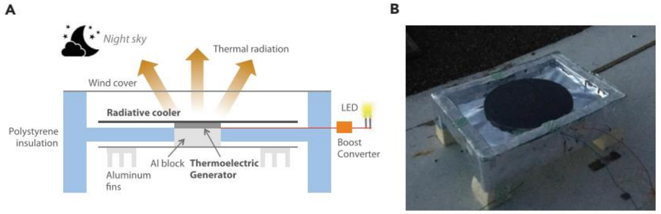


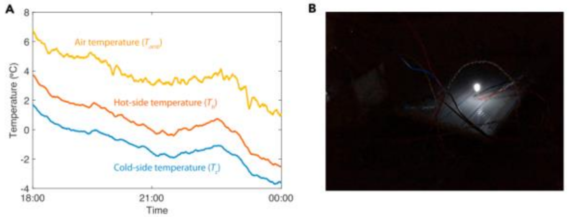
Z. ZHOU et al., Optics Express, 27, A404 (2019).

Enhancing thermoelectric generation

A. P. Raman et al., Joule, **3**, *1 (2019).*

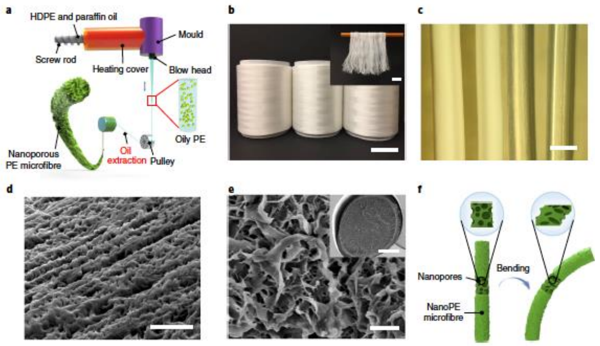
Generating light from darkness!

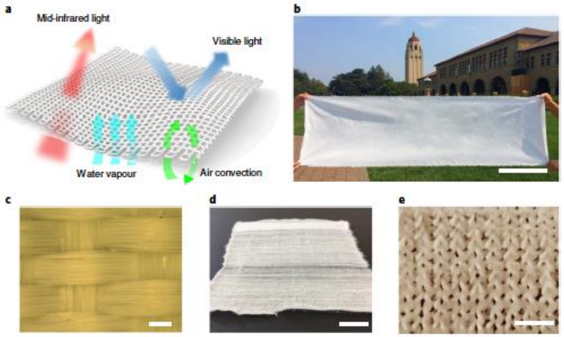




Human body cooling

Y. Peng et al, Nature Sustainability, **1**, *105 (2018).*



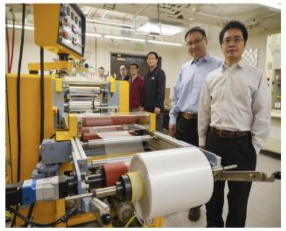


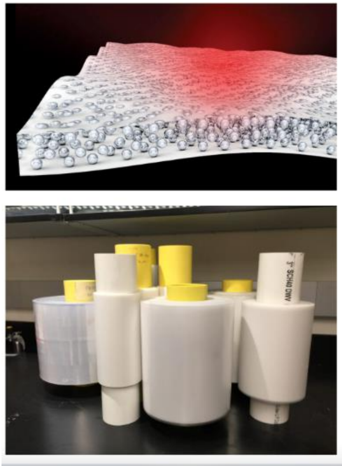
Start-UP

Sky-cool

Radi-cool

CEO: Ronggui Yang





Radiative cooling

J. Drévillon

Challenges and perspectives

Challenges

- Nanofabrication ⇒ Transition to the industrial scale.
- Nano/micro porous structure and nanofibers ⇒ Size control during elaboration (e.g electrospinning of different materials,…
- Outdoor use: UV radiation / humidity / dust,…
- More precise models for the transparency of the atmosphere and the radiative flux from the environment.

Perspectives

- Numerous proofs of concept: optimization and upscaling.
  - More generally: Optimization of the use of the cold darkness space!

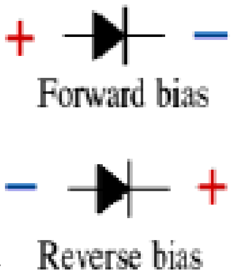
Thermotronics

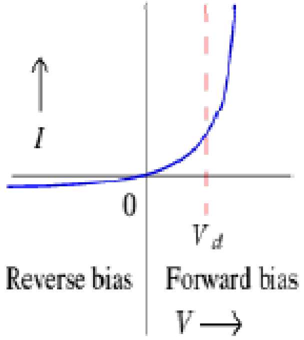
P. Ben-Abdallah
Y. Ezzahri
K. Joulain

Historical breakthroughs in electronics

Diode

F. Braun
1874

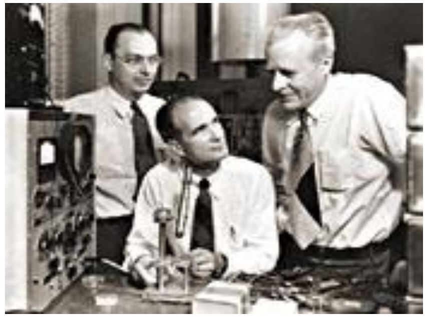


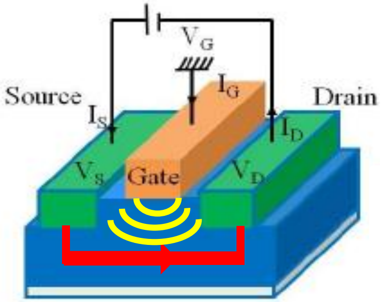


- **Perfect rectification of current**

Transistor (FET)

J. Bardeen, W. Brattain,
W. Shockley
1947-1951





- **Electrical switching**
- **Modulation**
- **Current amplification**

A variety of thermal analogues to the electronic components

*N. A. Roberts and D. G. Walker, IJTS, **50**, 648 (2011).*

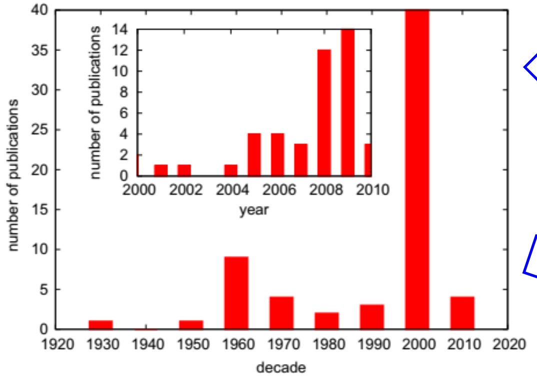


Fig. 1. Number of publications on thermal rectification per decade since 1936.

"1936: First experimental observation of thermal rectification"

*C. Starr, « The copper oxide rectifier », Journal of Applied Physics, **7**, 15-19 (1936).*

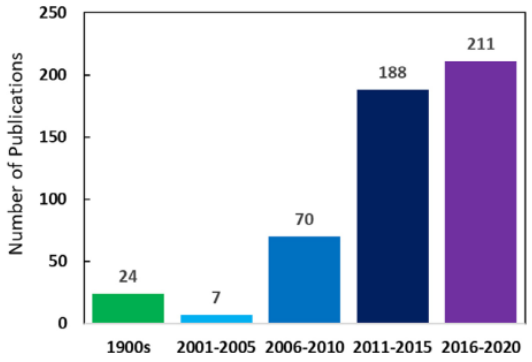


Fig. 2. Number of publications of thermal diode studies from the 1900s to present.

*M. Y. Wong, C. Y. Tso, T. C. Ho and H. H. Lee, IJHMT, **164**, 120607 (2021).*

Thermal diode
Thermal rectifier
Thermal switch
Thermal regulator
Thermal transistor
Thermal logical gates
Thermal memory
Thermal memristor
Thermal circuit

"No thermal analogue for the electrical inductance!!"

+

Thermal resistor
Thermal capacitor

GDR NAnoMaterials for Energy applications

Thermotronics

P. Ben-Abdallah
Y. Ezzahri
K. Joulain

Thermal rectifiers and thermal diodes

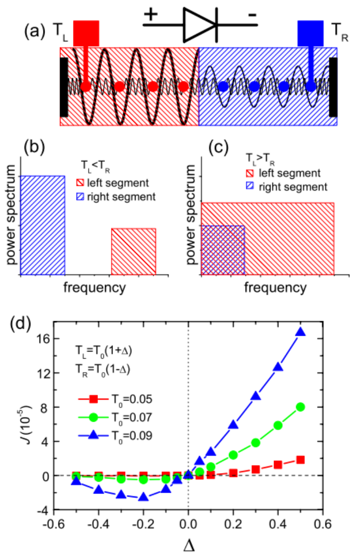
Different mechanisms

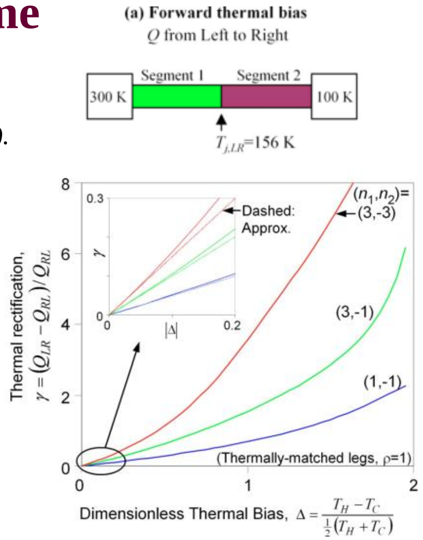
- **Conductive regime:** Asymmetric mismatch in phonon spectra (Nonlinear lattice coupled with harmonic spring) / Asymmetric Kaptiza resistance / Asymmetric temperature dependent thermal conductivity / Metal-insulator transition (hysteretic thermal behavior of Phase transition materials PTM)⟶ Phononics.
- **Radiative regime:** Resonance modes and broadband (selective emitters, superconductors and PTM) ⟶ Photonics.
- **Convective regime** also.

Conductive regime

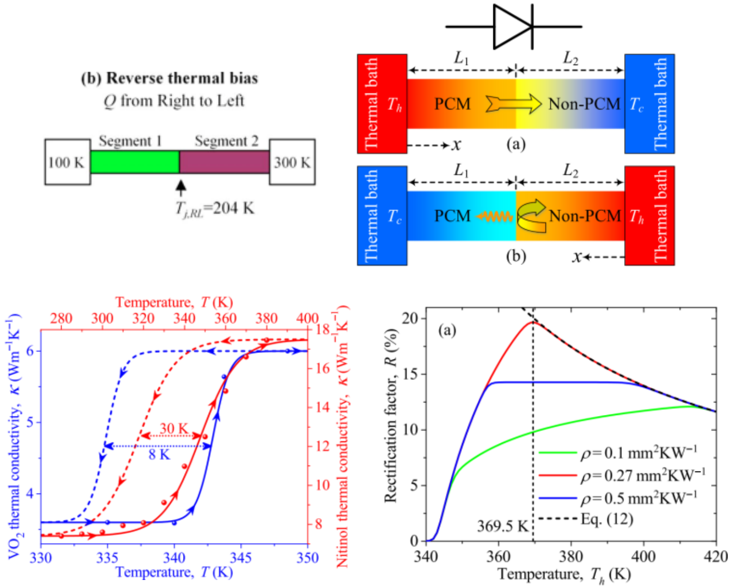
Theory

B. Li et al., PRL, **93**, 184301 (2004).





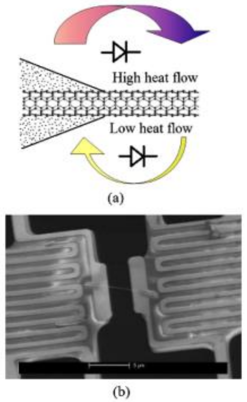
C. Dames, JHT, **131**, 061301 (2009).



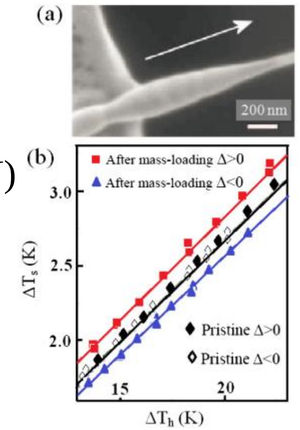
J. Ordonez-Miranda et al., JAP, **123**, 085102 (2018).

Experiment

C. W. Chang et al., Science, 3**14**, 1121 (2006).



Boron nitride (BN) nantube



Rectification factor

$$R=\frac{|\Phi_F-\Phi_R|}{Max\{\Phi_F,\Phi_R\}};\ \frac{|\Phi_F-\Phi_R|}{\Phi_{F,R}};\ \frac{|\Phi_F-\Phi_R|}{\Phi_F+\Phi_R};\ \frac{\Phi_F}{\Phi_R}$$

Limitations:

- Kapitza resistance
- Speed of phonons
- Phonon-phonon interactions with strong temperature gradients

Thermotronics

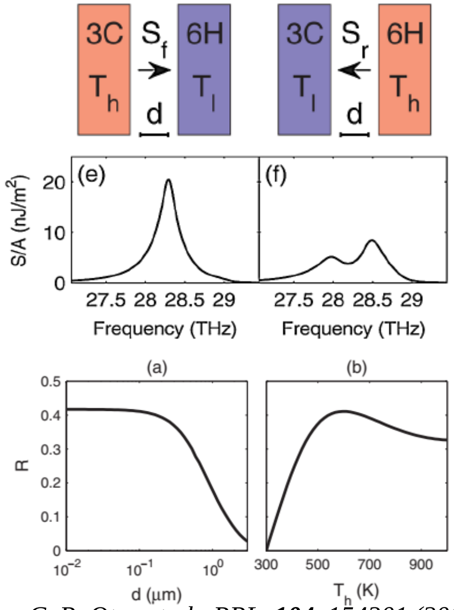
P. Ben-Abdallah
Y. Ezzahri
K. Joulain

Thermal rectifiers and thermal diodes

Radiative regime

Theory

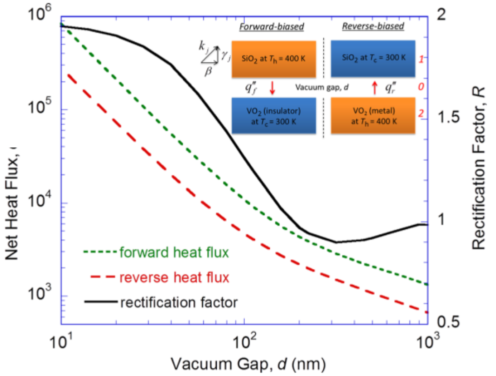
Two slabs of SiC-3C and SiC-6H



C. R. Otey et al., PRL, **104**, 154301 (2010).

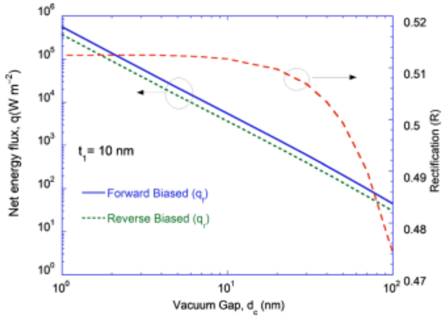
Thin film and bulk doped Si

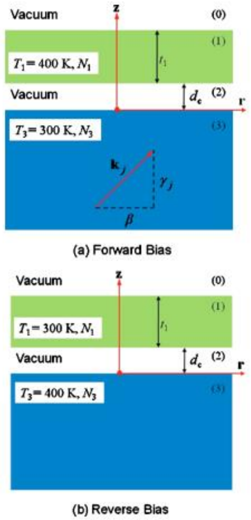
*Y. Yang et al., APL, **103**, 163101 (2013).*

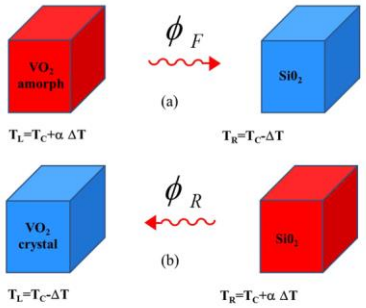


Near Field

*S. Basu and M Francoeur, APL, **98**, 113106 (2011).*

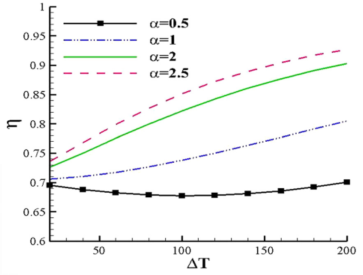


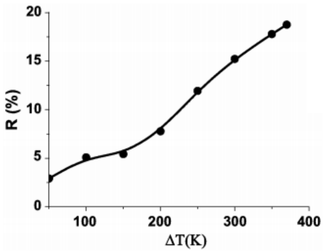




Near Field

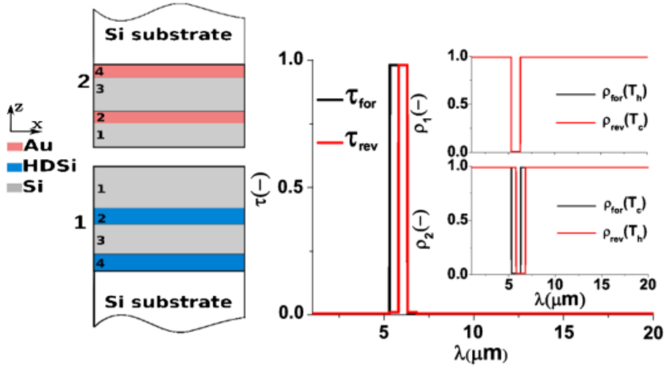
$$R = \frac{|\Phi_F - \Phi_R|}{Max\{\Phi_F, \Phi_R\}}$$



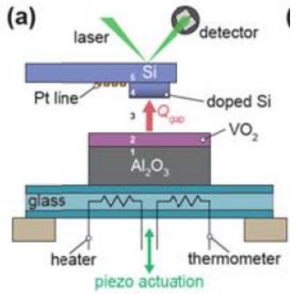


Far Field

*P. Ben-Abdallah and S. A. Biehs, APL, **103**, 191907 (2013).*



*E. Nefzaoui et al., AO, **53**, 3479 (2014).*



Near Field

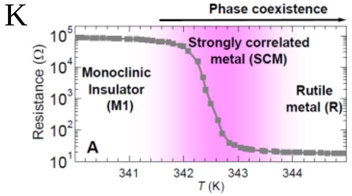
*A. Fiorino et al., ACS Nano, **12**, 5774 (2018).*

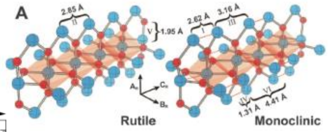
Experiment

Using phase change (transition) materials or superconductors

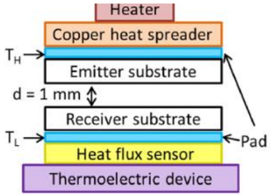
Mott transition at 340 K

VO_2

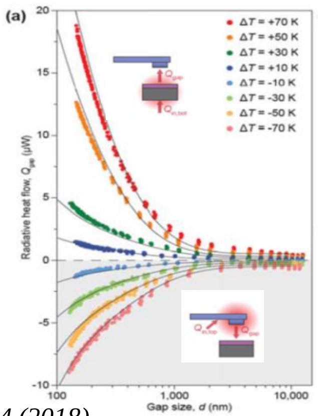


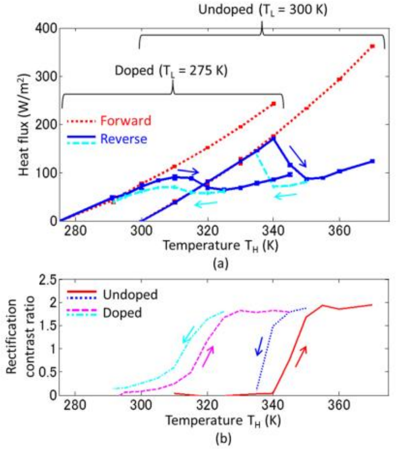


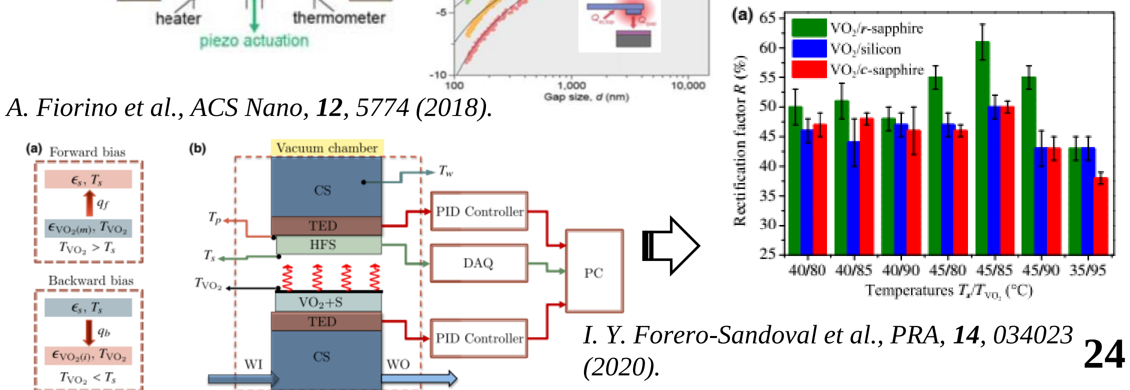
Far Field



*K. Ito et al., APL, **105**, 253503 (2014).*







*I. Y. Forero-Sandoval et al., PRA, **14**, 034023 (2020).*

NAMe

GDR NAnoMaterials for Energy applications

Thermotronics

Thermal transistors

Conductive regime

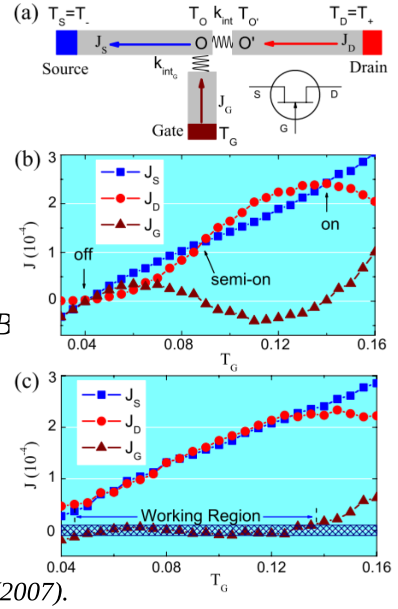
*B. Li et al., APL, **88**, 143501 (2006).*

"Thermal transistor effect ↔ negative differential thermal resistance"

Amplification factor

$$\alpha \equiv \left|\frac{\partial J_D}{\partial J_G}\right| = \left|\frac{R_S}{R_S + R_D}\right| > 1 \text{ SSS } R_S \text{ or } R_D < 0$$

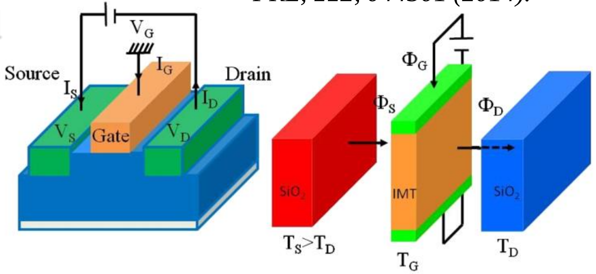
*N. Li, J. Ren, L. Wang, G. Zhang, P. Hänggi and B Li, Review of Modern Physics, **84**, 1045 (2012).*

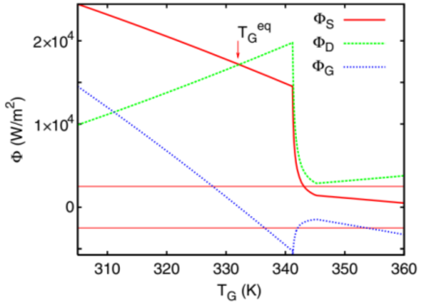


Radiative regime

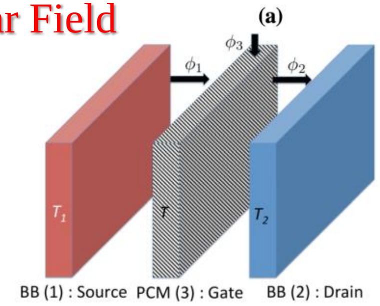
*P. Ben-Abdallah and S. A. Biehs, PRL, **112**, 044301 (2014).*

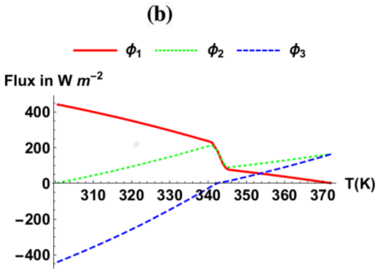
Near Field

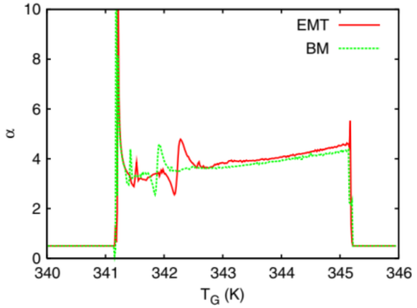


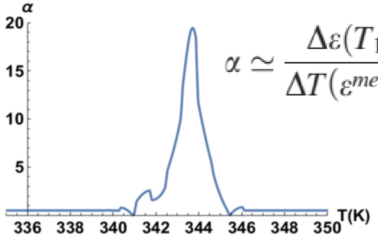


Far Field









$$\alpha \simeq \frac{\Delta\varepsilon(T_1 - T_c)}{\Delta T(\varepsilon^{met} + \varepsilon^{diel})}$$

*K. Joulain et al., APL, **106**, 133505 (2015).*

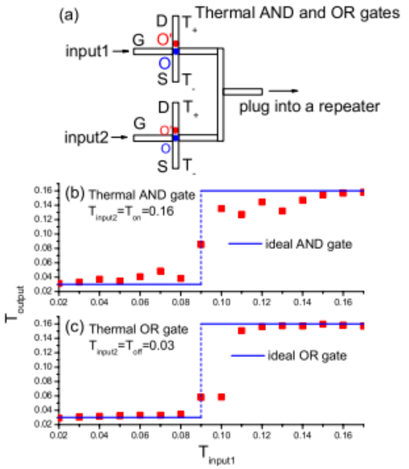
Operating modes:

1-Thermal switch
2-Flux modulation
3-Flux amplification

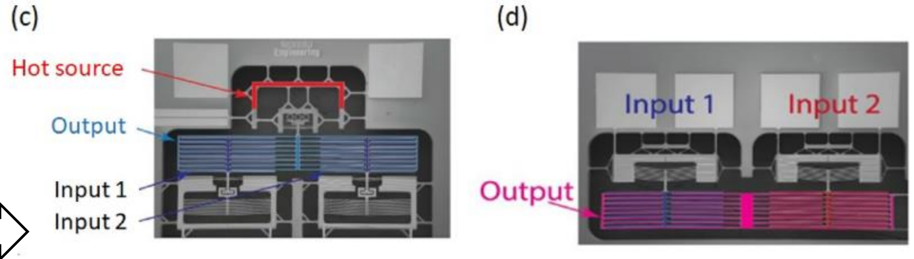
Thermal logical gates and memories

Conductive regime

*L. Wang and B. Li, PRL, **99**, 177208 (2007).*

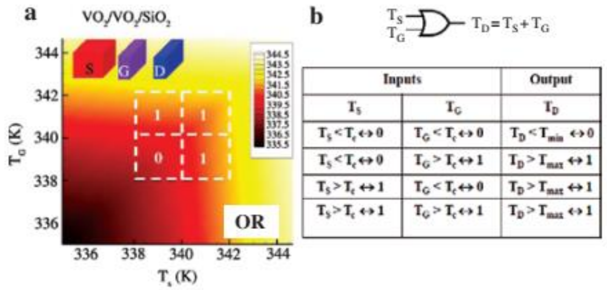


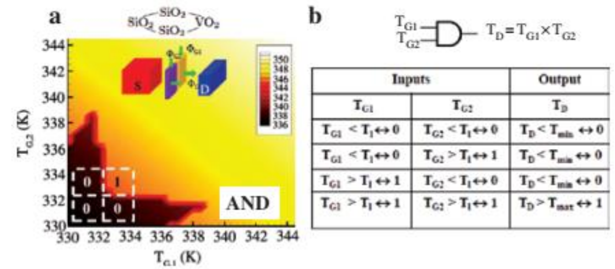
SEM images of "AND" and "OR" NanoThermoMechanical gates



*A. Hamed and S. Ndao, Scientific Reports, **10**, 2437 (2020)*

Radiative regime





*P. Ben-Abdallah and S. A. Biehs, PRB, **94**, 241401(R) (2016).*

N A M e

GDR NAnoMaterials for Energy applications

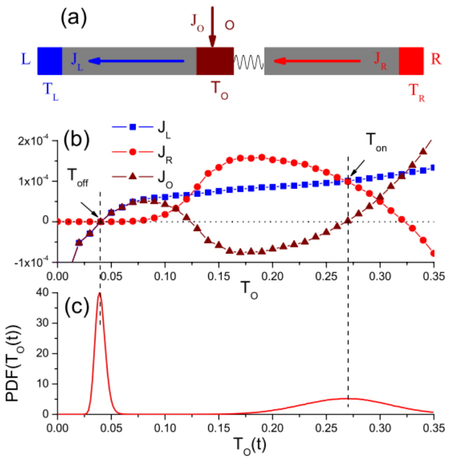
Thermotronics

P. Ben-Abdallah
Y. Ezzahri
K. Joulain

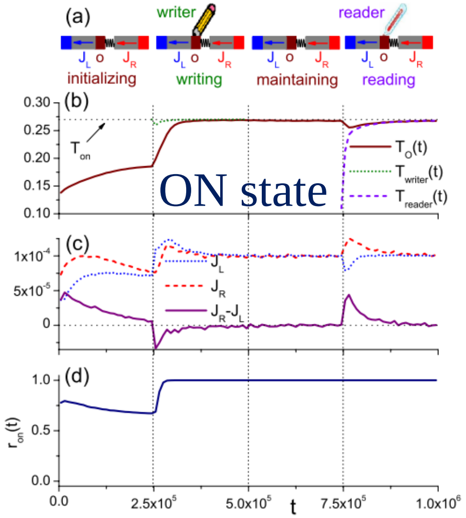
Thermal logical gates and memories

Conductive regime

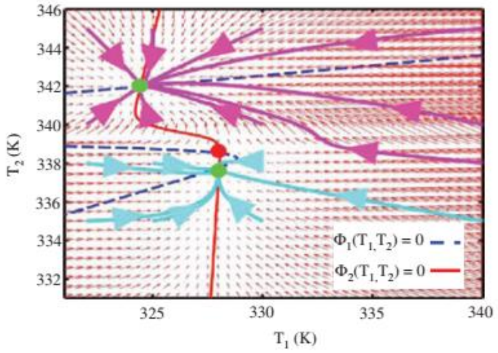
Theory

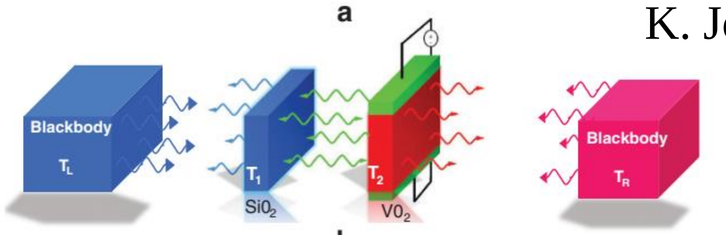


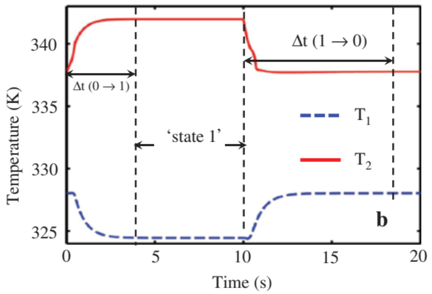
L. Wang and B. Li, PRL, **101**, 267203 (2008).



Radiative regime



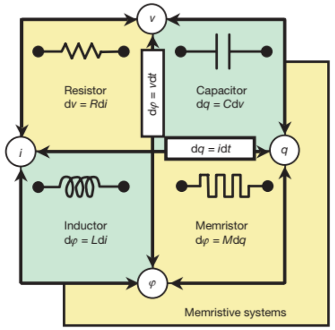




V. Kubytskyi et al., PRL, **113**, 074301 (2014).

Thermal memristor

Memristor = Memory resistor



Chua's Memristor

$$v = \mathcal{R}(w)i$$

$$\frac{\mathrm{d}w}{\mathrm{d}t} = i$$

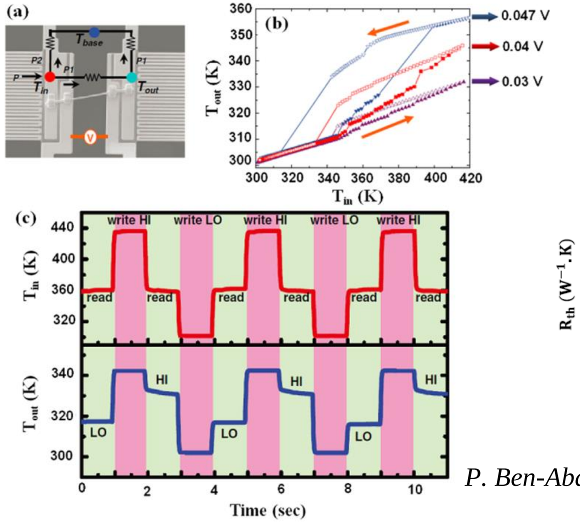
Memristive system

$$v = \mathcal{R}(w,i)i$$

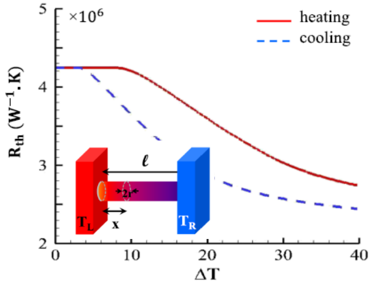
$$\frac{\mathrm{d}w}{\mathrm{d}t} = f(w,i)$$

- W is a state variable of the device.
- R is a generalized resistance.

Experiment

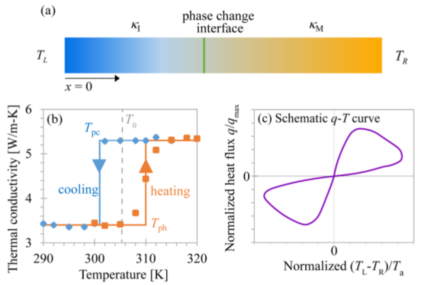


R. Xie et al., Adv. Funct. Mater, **21**, 1602 (2011).



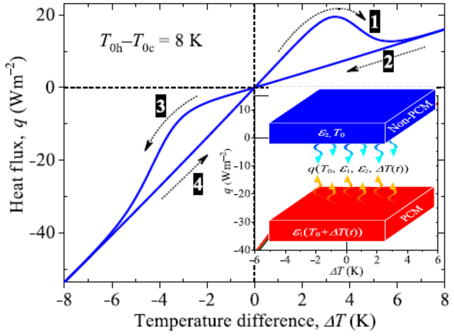
P. Ben-Abdallah, AIP Advances, **7**, 065002 (2017).

Conductive regime



F. Yan et al., JAP, **125**, 025109 (2019).

Radiative regime



State variable = volume fraction f

J. Ordonez-Miranda et al., PRL, **123**, 025901 (2019).

N A M e

GDR NAnoMaterials for Energy applications

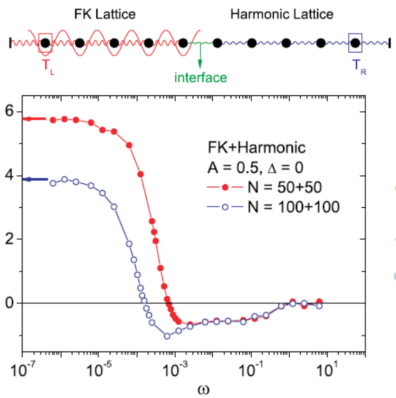
Thermotronics

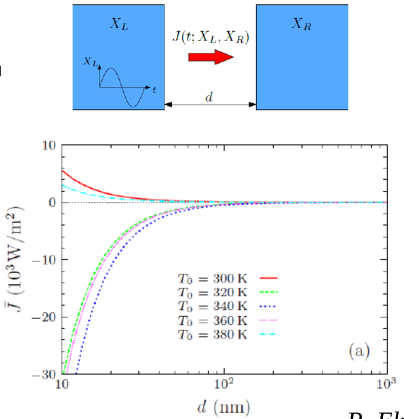
P. Ben-Abdallah
Y. Ezzahri
K. Joulain

Active control of heat flux

Shuttling and ratcheting

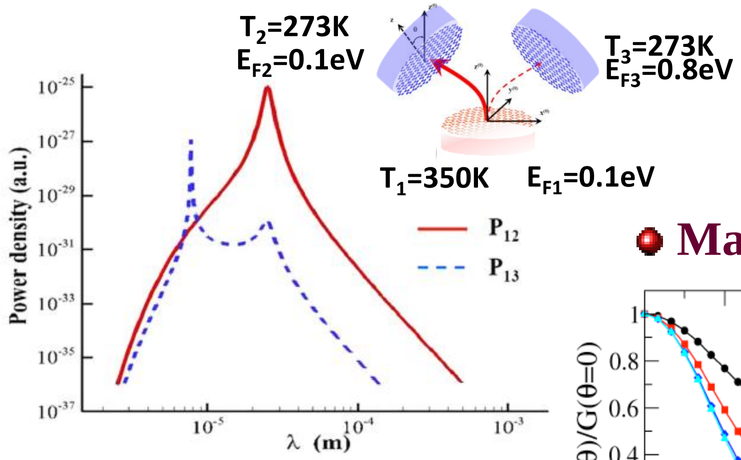
Pumping heat against the thermal bias





N. Li et al. Phys. Rev. E **80**, 011125 (2009); N.-B. Li et al. Europhys. Lett. **84**, 40009 (2008);
I. Latella et al. Phys. Rev. Lett. **121**, 023903 (2018).

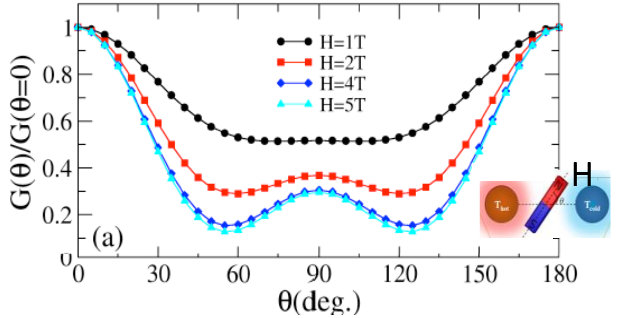
Heat splitting



P. Ben-Abdallah et al. APL, **107**, 053109 (2015).

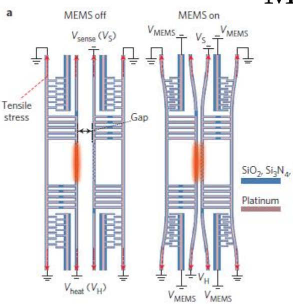
R. Ekeroth et al. ACS Photonics, **5**, 705, (2018).
I. Latella et al. PRL **118**, 173902 (2017).

Magnetic control

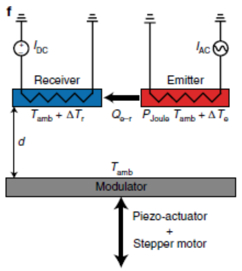


Mechanical control

MEMS/NEMS

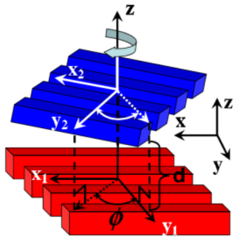


R. St. Gelais et al., Nature Nanon **11**, 515 (2016).



D. Thompson et al., Nat. Nano, **15,** 99 (2020).

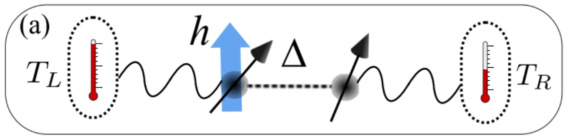
Gratings rotation



S.-A. Biehs et al. APL, **98**, 243102 (2011).

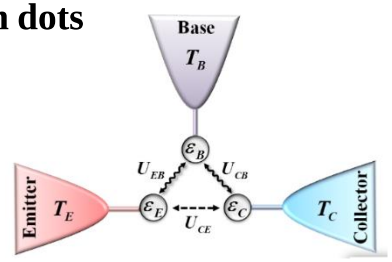
How about the quantum regime?

Thermal diode



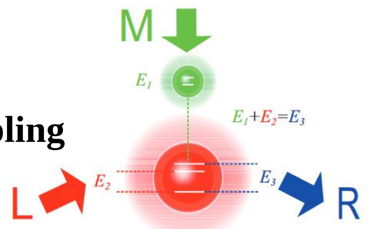
T. Werlang et al., PRE, **89**, 062109 (2014).

Using Colomb-coupled quantum dots



Y. Zhang et al., EPL, **122**, 17002 (2018).

Using Qubit-Qutrit coupling



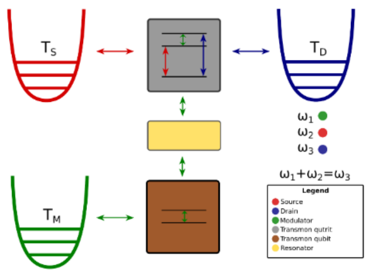
B. Guo et al., PRE, **98**, 022118 (2018).

Thermal transistor

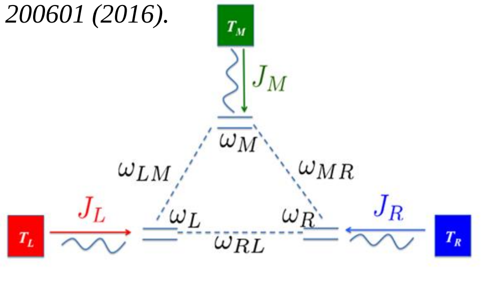
K. Joulain et al., PRL, **116**, 200601 (2016).

Using Superconductors

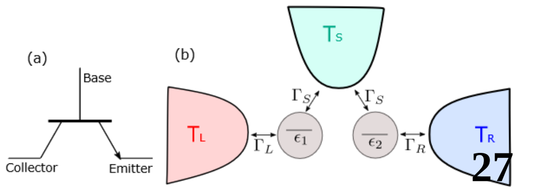
M. Majland et al., PRB **101**, 184510 (2020).



Using Qubits



G. Tang et al., Eur. J. Phys. B, **92**, 27 (2019).



GDR NAnoMaterials for Energy applications

Thermotronics

P. Ben-Abdallah
Y. Ezzahri
K. Joulain

Challenges and perspectives

Challenges

➤ **The operating time scale in nanostructures (~ms to s) is limited by the thermal inertia.**

Perspectives

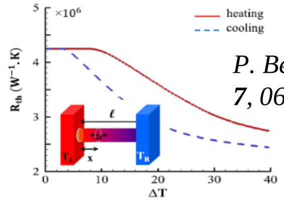
➤ **Extension of the developed concepts to the conductive regime using Phase Transition Materials (e.g VO_2).**

➤ **Exploring and deepening the analysis of the dynamical regime.**

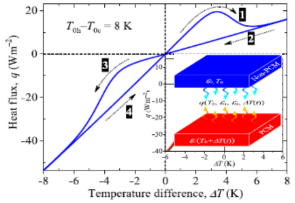
➤ **Towards smart hybrid circuits and structures optimizing heat management and electronic operation …**

➤ **Towards a full heat information treatment structure…**

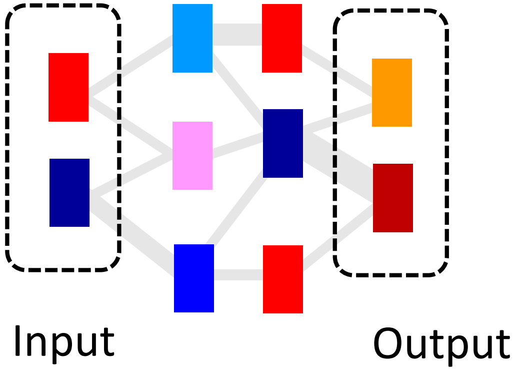
Memristive behavior



*P. Ben-Abdallah, AIP Advances **7**, 065002 (2017).*

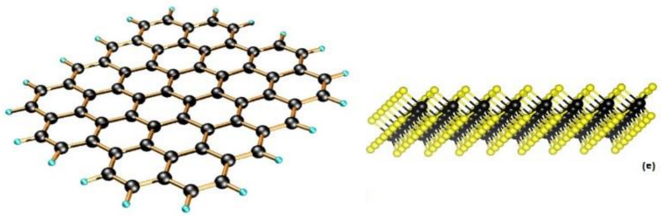


*J. Ordonnez-Miranda et al., PRL **123**, 025901 (2019).*



Neuromorphic computing

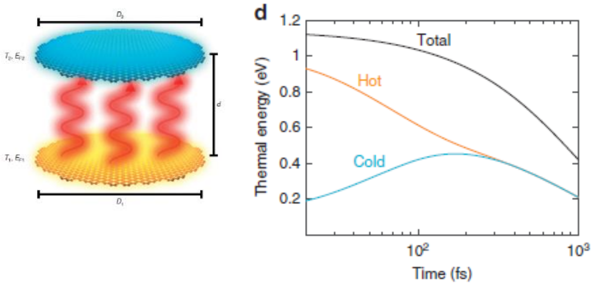
Two dimensional materials



➤ **Transition metal dichalcogenide monolayers could allow to design thermal transistor operating at submicrosecond scale**

Systems far from equilibrium

*R. Yu, et al. Nat Commun **8**, 2 (2017).*



➤ **Electrons and phonons at different temperatures.**

➤ **Heat flux control at pico and subpicosecond scale…**

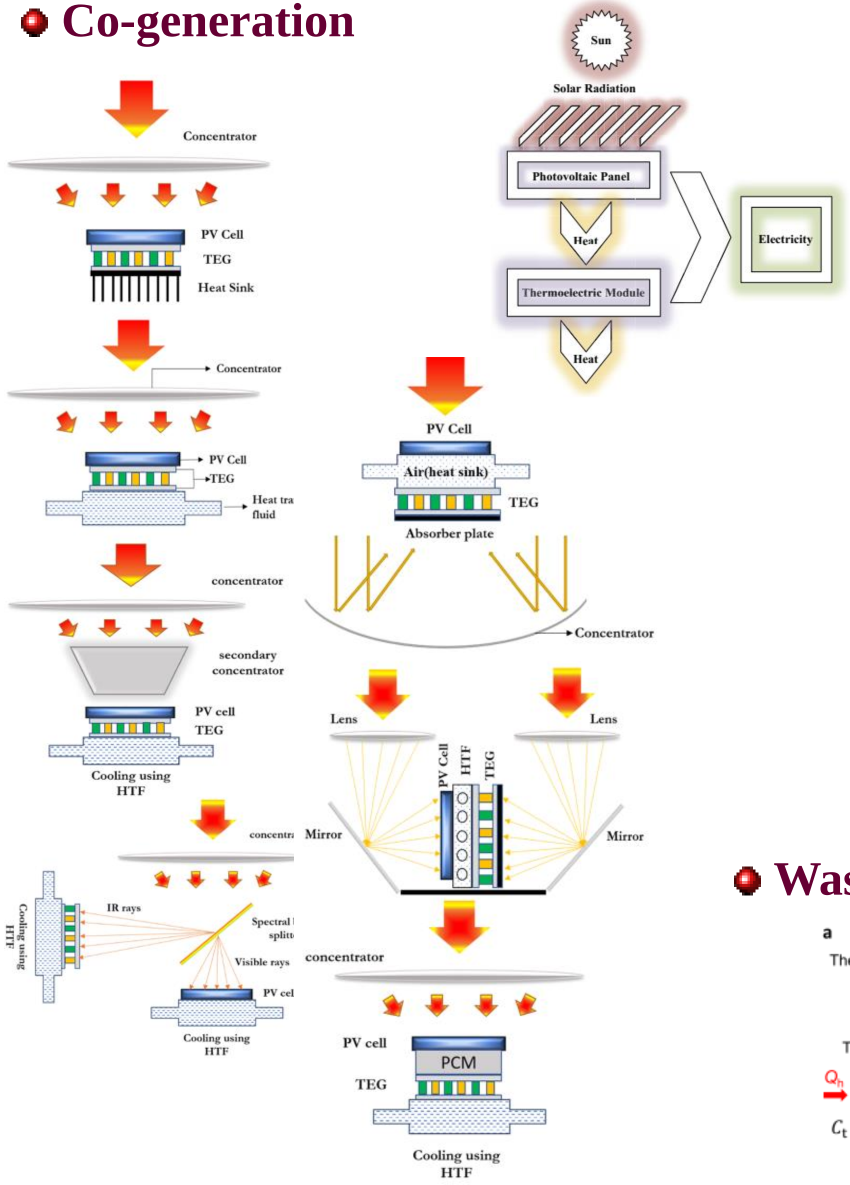
GDR NAnoMaterials for Energy applications

Hybrid applications

P. Ben-Abdallah
Y. Ezzahri
K. Joulain

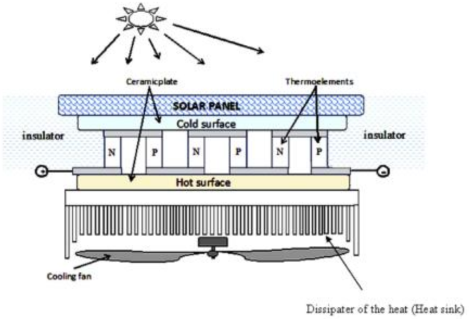
Hybrid solar PV-TE systems

- **Co-generation**



*S. S. Indira et al., Solar Energy, **201**, 122 2020.*

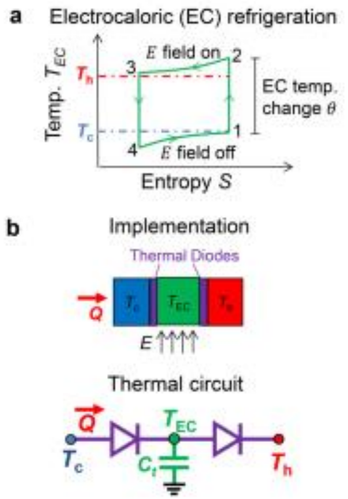
- **Cooling**



*M. Benghanem et al., Renewable Energy, **89**, 51 2016.*

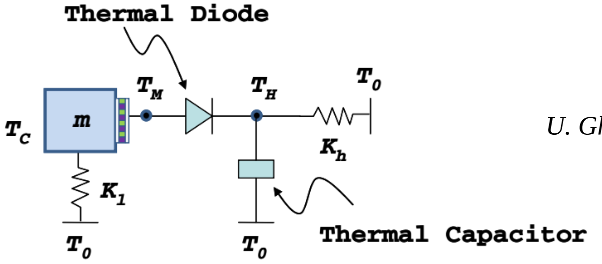
Hybrid Thermotronics applications and beyond!

- **Solid-state refrigeration using thermal diodes**



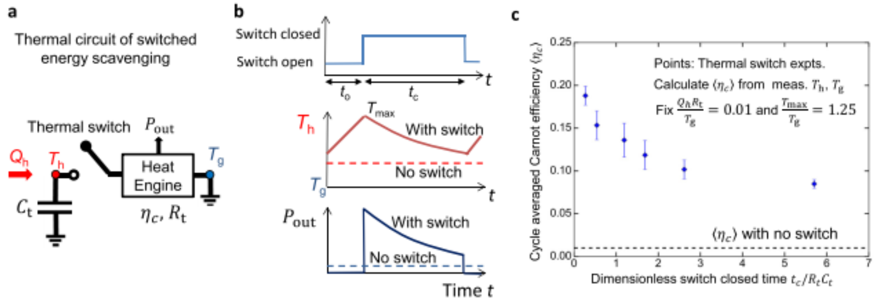
*G. Wehmeyer, T. Yabuki, C. Monachon, J. Wu and C. Dames, Applied Physics Reviews, **4**, 041304 (2017).*

- **Enhancing thermoelectric refrigeration**



*U. Ghoshal and A. Guha, JEM, **38**, 1148 2009.*

- **Waste heat scavenging using switchable and nonlinear thermal devices**



*G. Wehmeyer, T. Yabuki, C. Monachon, J. Wu and C. Dames, Applied Physics Reviews, **4**, 041304 (2017).*