GDR NAME

2nd plenary meeting: October 04-06 2021

Workshop 4: Thermal Management

October 5th 2021

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

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
- 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 transistors
  - Thermal logical gates and memories
  - Thermal memristors
  - Active control of heat flux
  - How about the quantum regime?
  - Challenges and perspectives
- Radiative cooling and heating
  - Principles
  - Applications
    - Daytime radiative cooling
    - Nighttime radiative cooling
    - Radiative condensers (black silicon)
  - Challenges and perspectives

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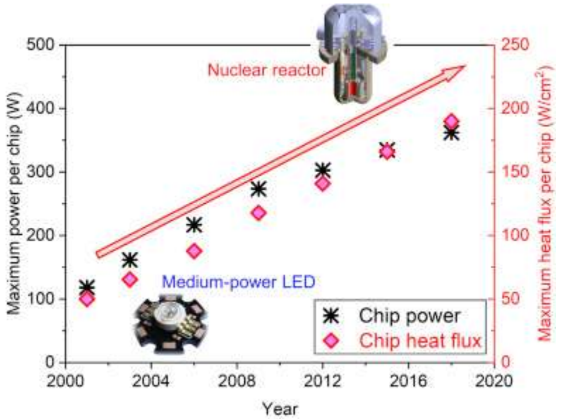
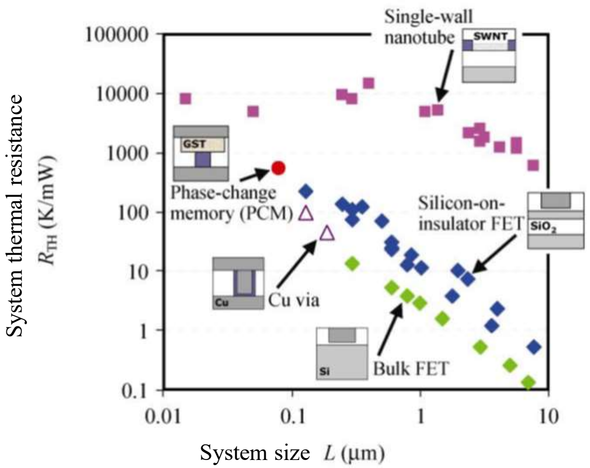
Overview

Orders of magnitude



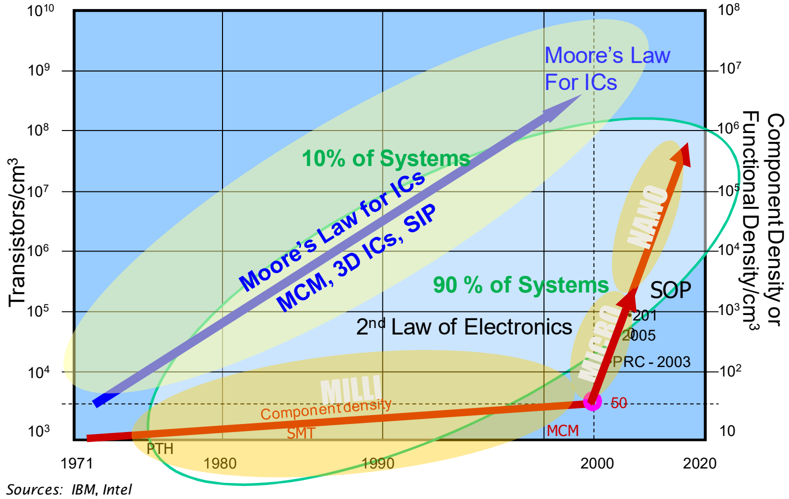
*X.-H. Yang and J. Liu, in Advances in Heat Transfer, **50**, 187–300 (2018)*

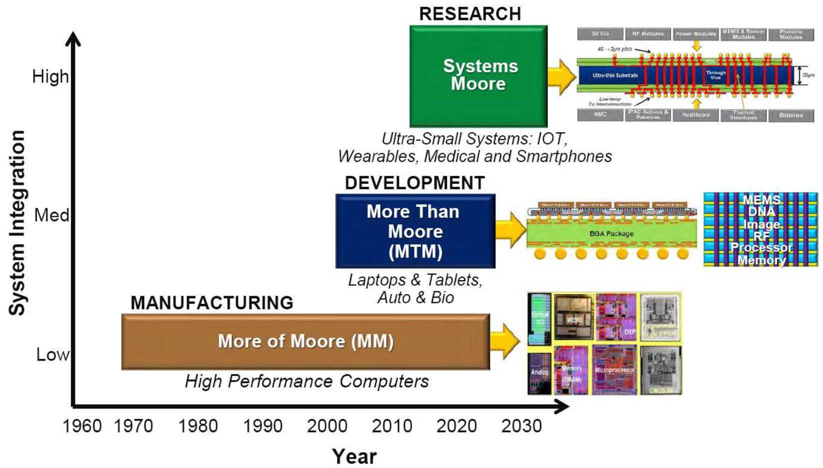


*E. Pop, Nano Res (2010) **3**: 147–169*

Trends

From "more Moore" to "system Moore"

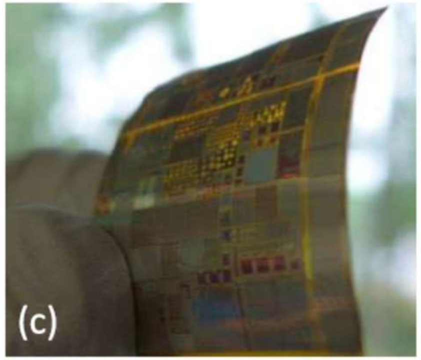


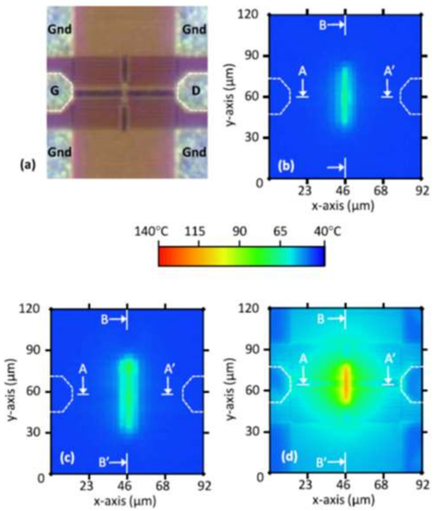


R. Tummala, System-On-Package (SOP), Mc Graw-Hill 2008

Trends

Flexible electronics





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

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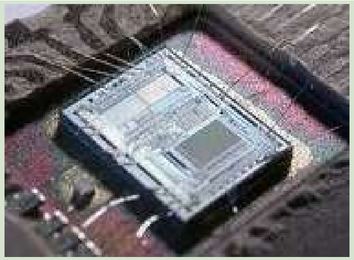
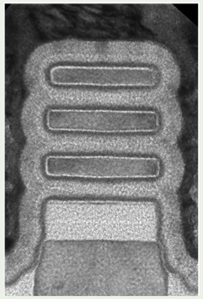
Thermal Management for IC

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

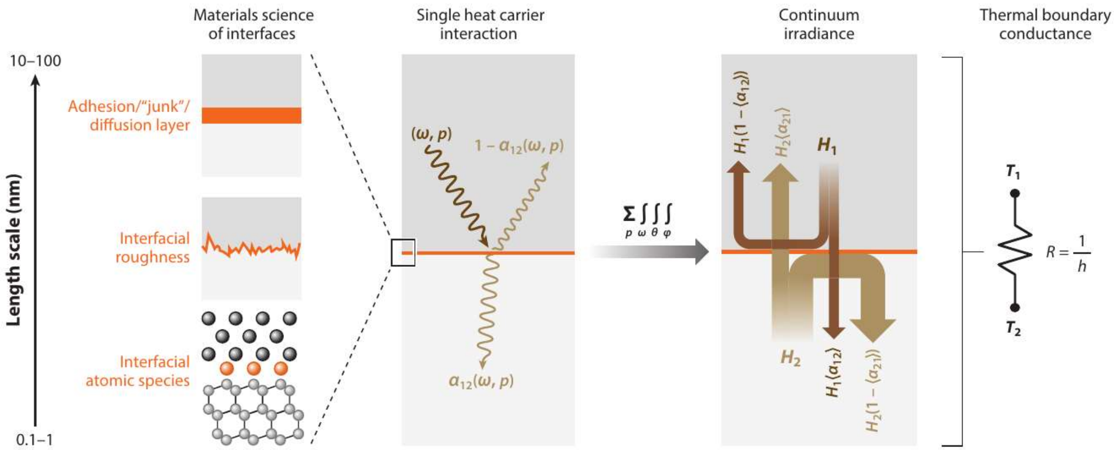
N. Horny

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

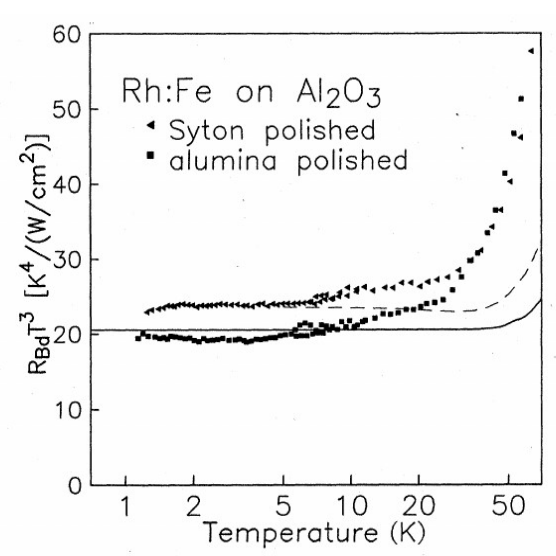
- Quality of the interface (roughness, oxyde)
- Strength of interatomic interactions at the interface
- Dispersion and density of states (DOS) for energy carriers
- Temperature
- Pressure

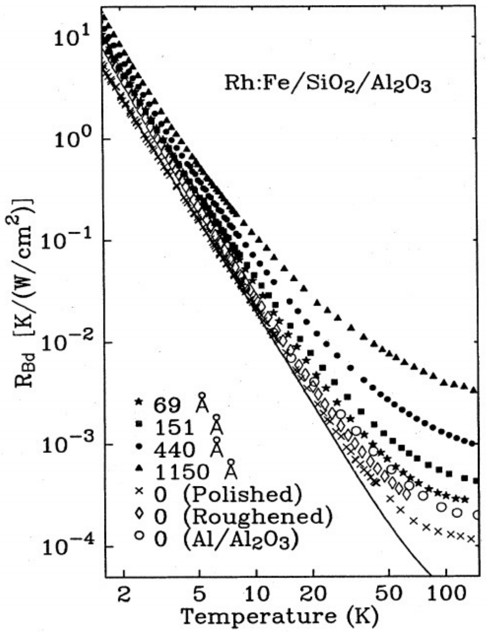
- *Hopkins, P. E. (2013). "Thermal transport across solid interfaces with nanoscale imperfections: effects of roughness, disorder, dislocations, and bonding on thermal boundary conductance." International Scholarly Research Notices, 2013.*
- *Monachon, C. et al. , Annual Review of Materials Research, **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 interface resistance / conductance

T^3 dependence at low T

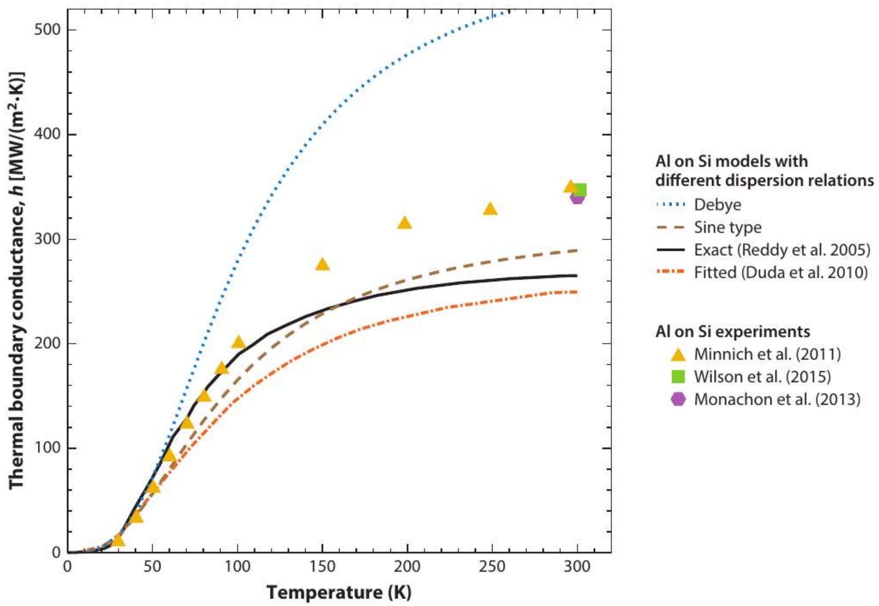
« Thermal resistance at interfaces »
E. T. Swartz and R. O. Pohl, Appl. Phys. Lett. ***51****, 2200 (1987)*
« Thermal boundary resistance »
E. T. Swartz and R. O. Pohl, Rev. Mod. Phys. ***61****, 605 (1989)*





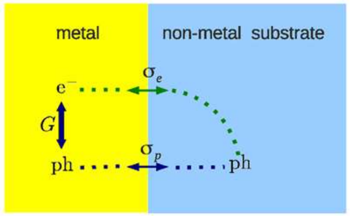
Diffuse Mismatch model

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

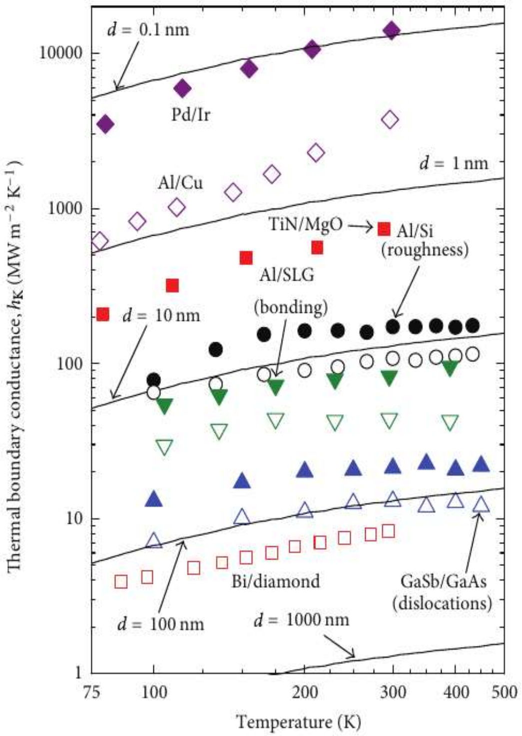


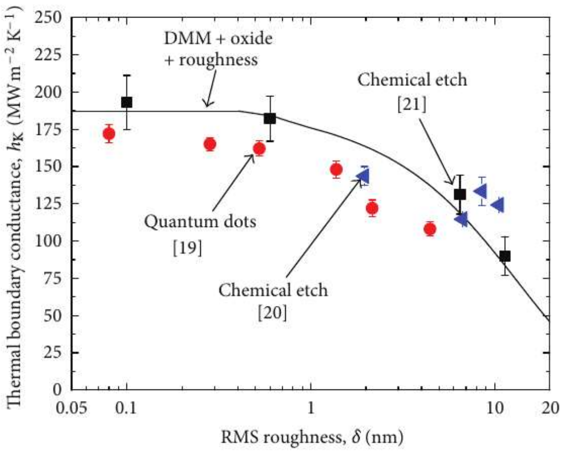
Thermal interface resistance / conductance

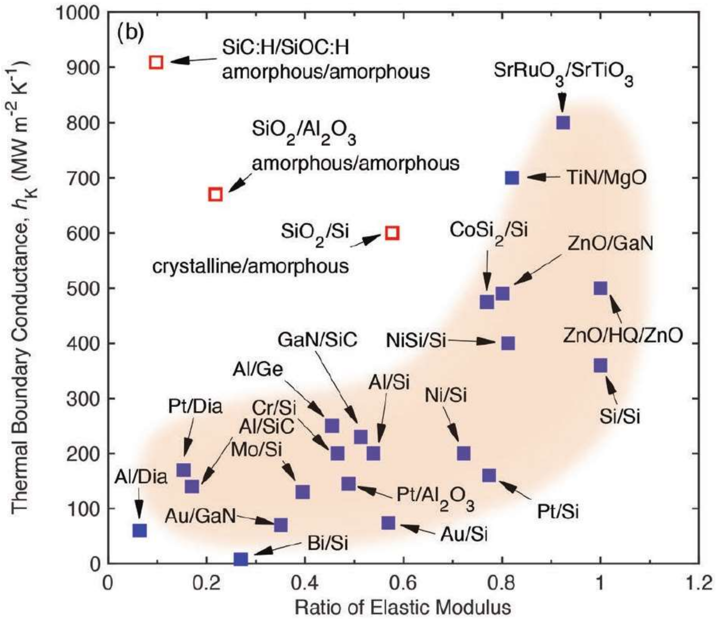
- metal-metal : TBC is dominated by electron transport
- metal-nonmetal : TBC is dominated by phonon transport
- Effect of roughness
- Effects of Lattice Dislocations



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







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.

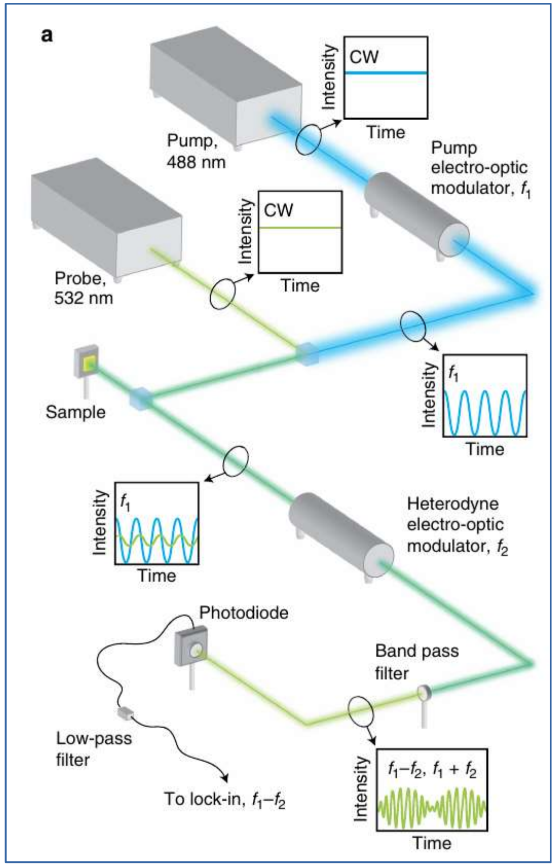
*A. Giri, and P. E. Hopkins, Advanced Functional Materials, **30**(8), 1903857 (2020)*

Thermal Management for IC

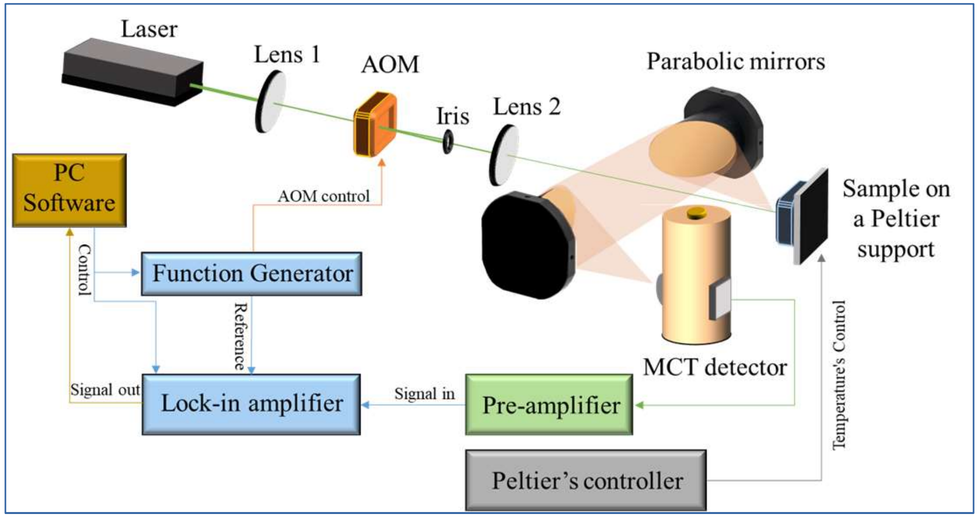
N. Horny

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

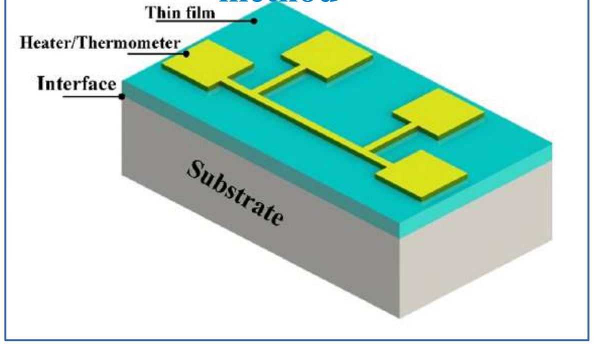
Time or frequency domain ThermoReflectance



Time or frequency domain Photothermal Radiometry



3ω method



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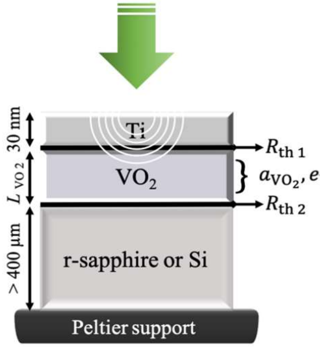
Thermal Management for IC

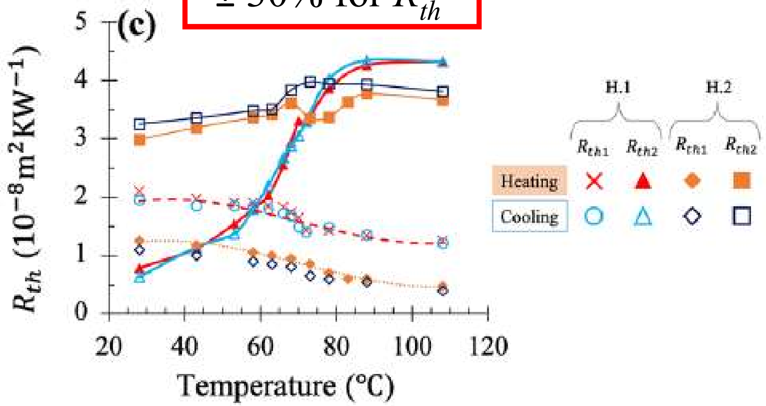
N. Horny

Applications • Phase Change Materials devices

Thermophysical characterisation of VO_2 thin films hysteresis

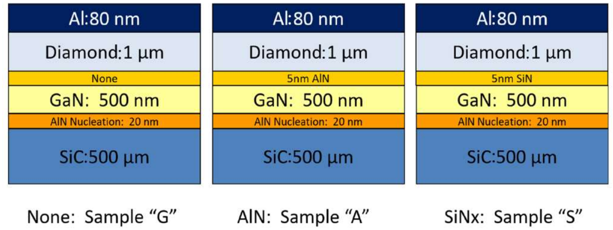


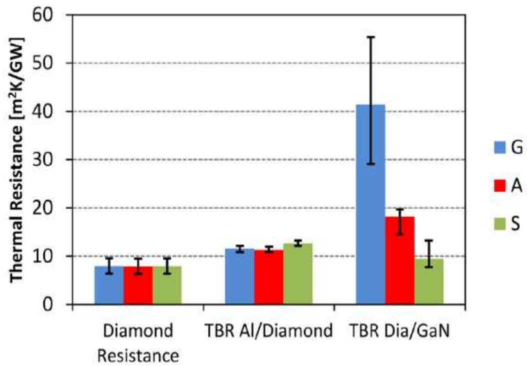
± 30% for R_{th}



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

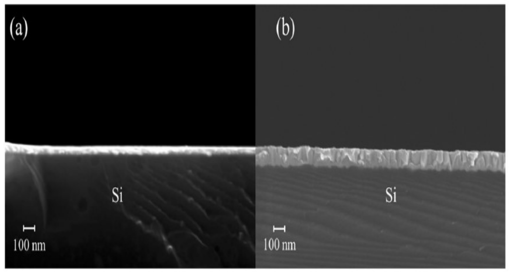
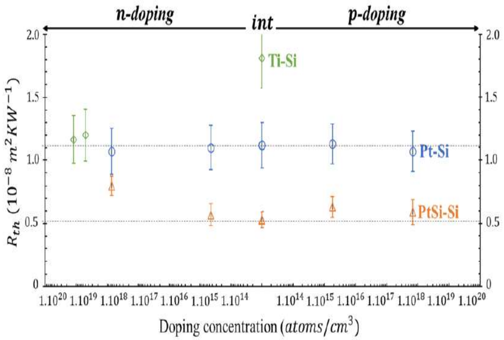


Figure 3. Example of a SEM images for the S3 samples: (**a**) unannealed Pt-Si and (**b**) annealed PtSi-Si samples.



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

Thermal Management for IC

J.-F. Robillard

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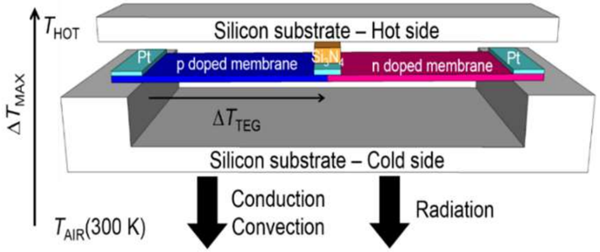
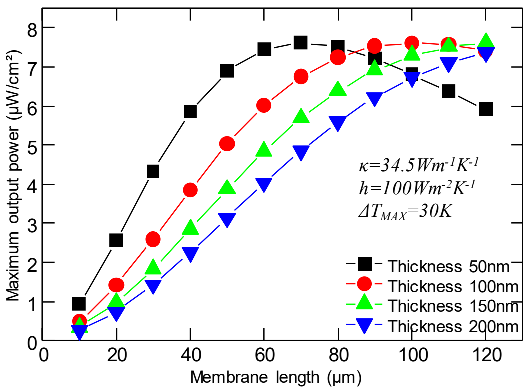
Applications — Thermoelectric Energy harvesting

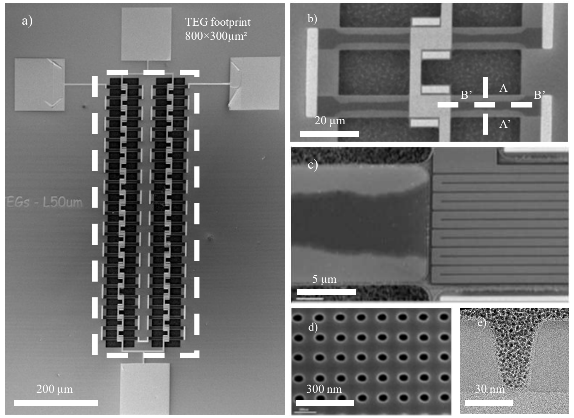
Attempts to integrate membrane-like or NW TE Converters lead to new thermal management issues.
Mainly related to the vertical to horizontal heat flux redirection
And air exchange.



Device optimization

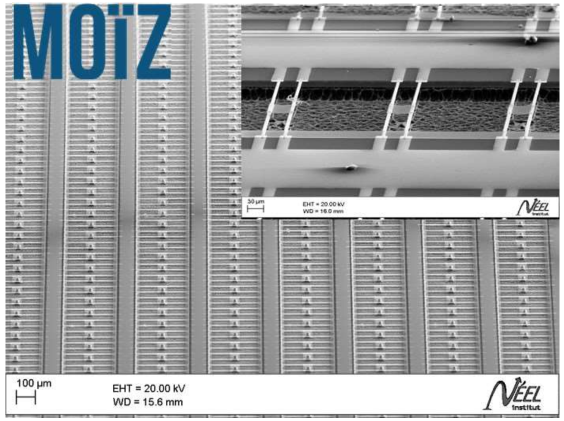


c-Si Membranes



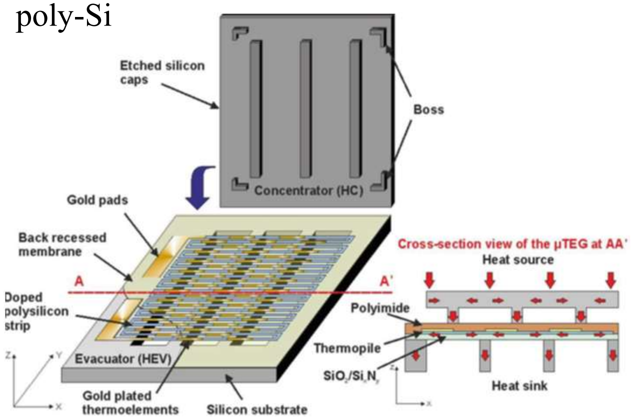
*M. Haras et al. IEEE Electron Device Letters, **37**, 1358 (2016)*
T. M. Bah et al. (in prep.)

Bi2Te3 — Air flow



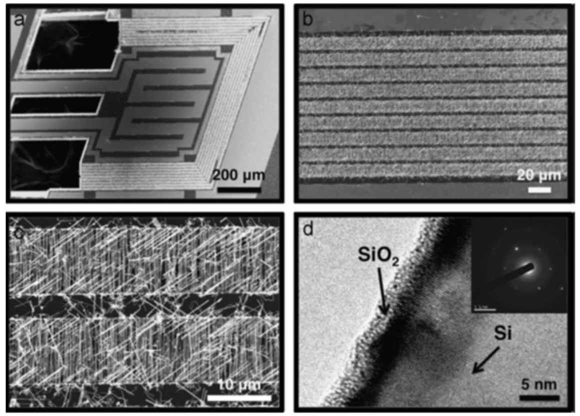
*D. Tainoff etal . Nano Energy **57** 804–810 (2019)*

poly-Si



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

c-Si NW



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

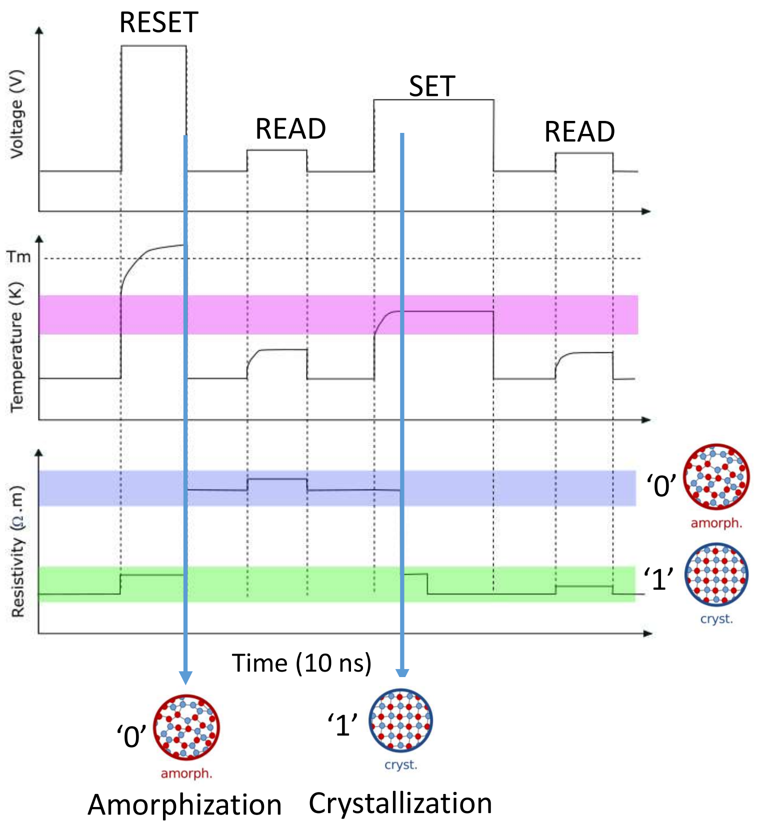
GDR NAnoMaterials for Energy applications

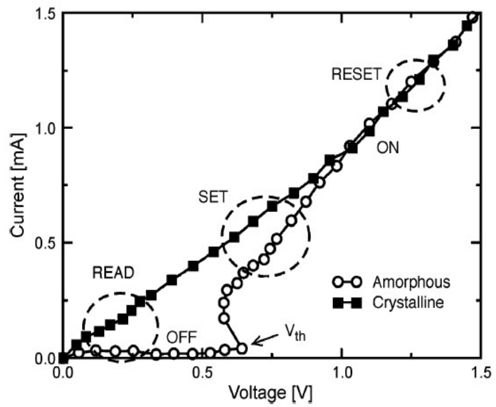
Thermal Management for IC

J.-F. Robillard
R. Simola

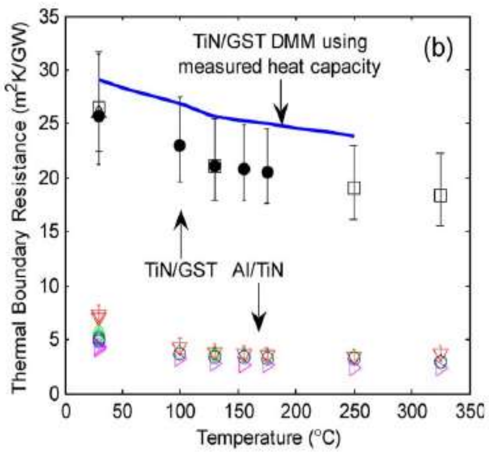
Applications — Phase Change Materials devices

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

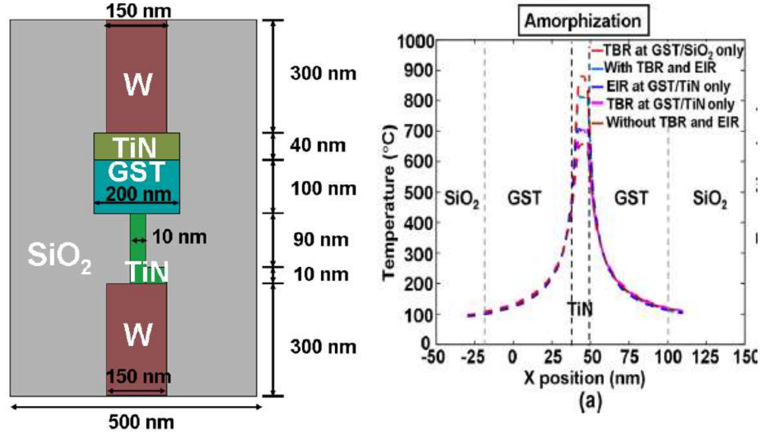




A. Pirovano et al IEEE Trans. Electron Devices, ***51****, 452 (2004).*

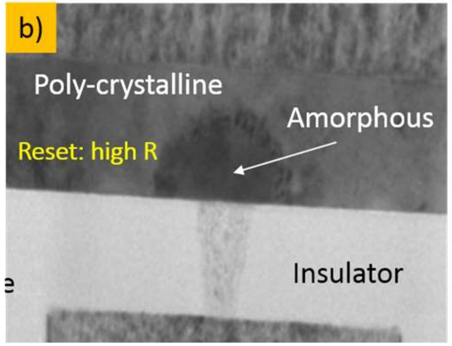


John P. Reifenberg, et al. IEEE Electron Device Letters, ***31****, NO. 1, (2010)*



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

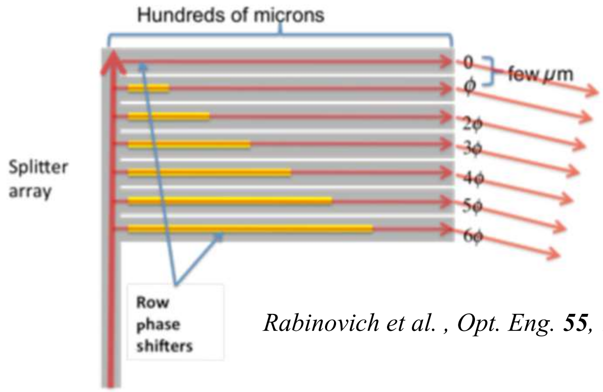
Thermal Management for IC

J.-F. Robillard
S. Monfray

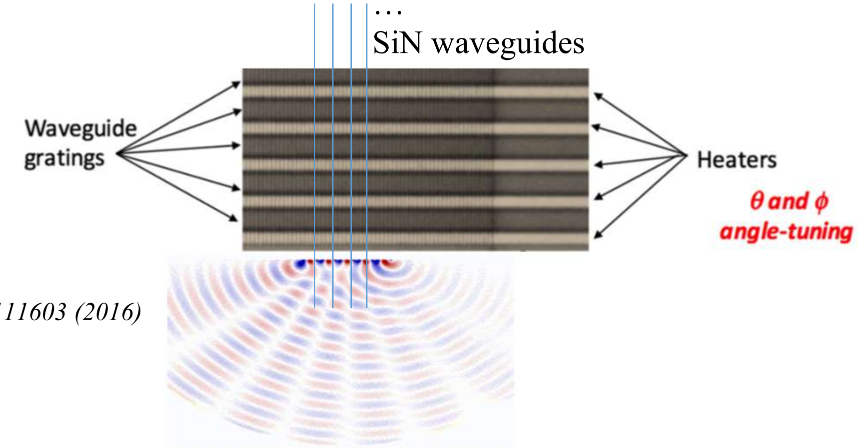
Applications

LIDAR: Beam steering with thermo-optical waveguides

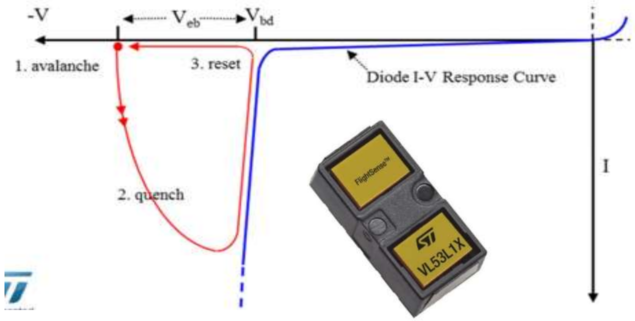
- For IR (905 nm)
- SiN waveguides
- Thermo-optical modulation
- Challenge=go to high frequencies (10-50kHz)
- Need for thermal optimization



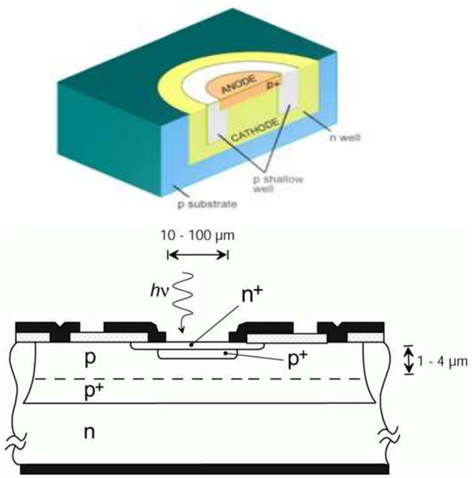
*Rabinovich et al. , Opt. Eng. **55**, 111603 (2016)*

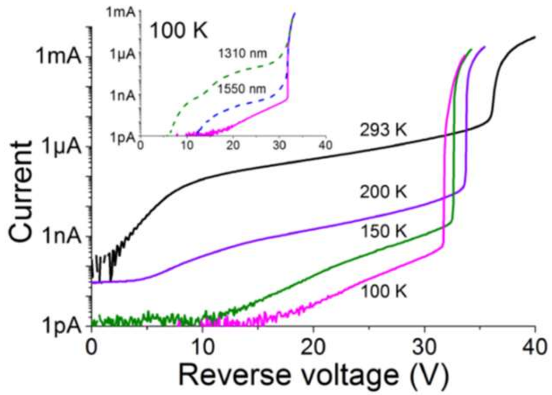


Detection and imaging : Single Photon Avalanche Diodes



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

Thermal Management for IC

J. Maire

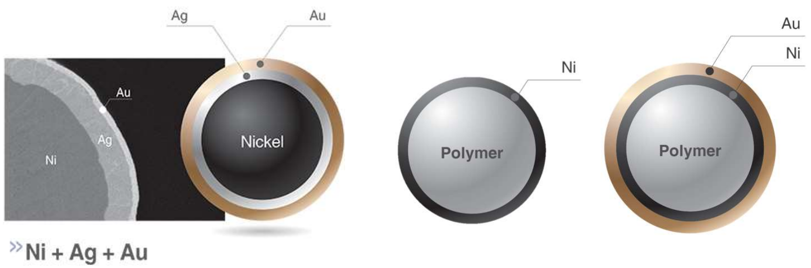
Techniques • Passive: Thermal interface materials

TIMs for 5G/AI/Semiconductors

Electrically conductive adhesives - alternative to solders (electronic packaging)

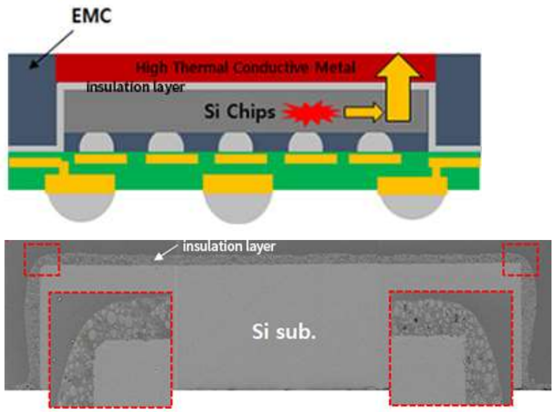
Elastomer socket powder – semiconductor testing

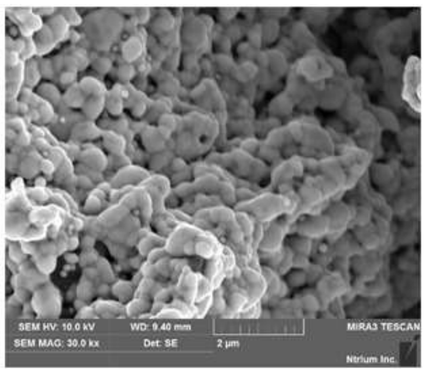
Conductive powder - touch screen panels



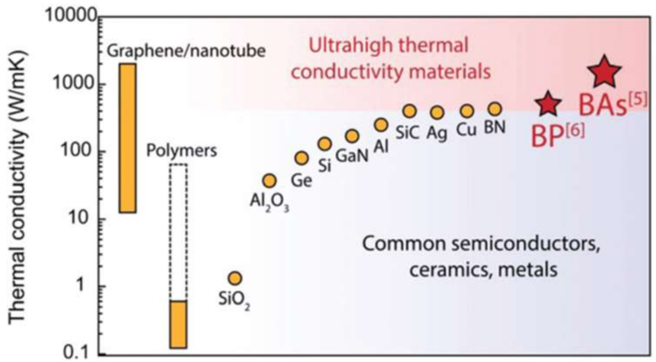
High thermal ceramic paste for spray – electrical insulator / spray

High Thermal Ag Sintering Paste – high thermal conductivity





Ultrahigh phonon conductivity materials

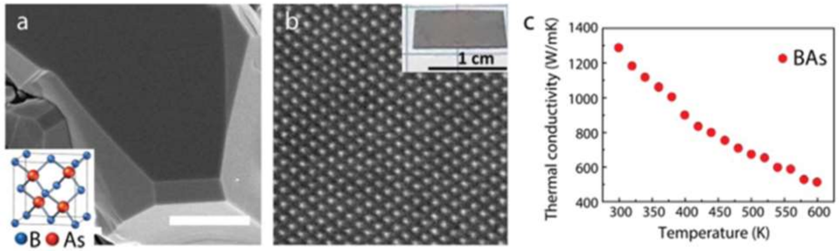


Primarily Synthetic diamond, BN, SiC, Ag, Al, and Cu

Coefficient of thermal expansion should match the heat source

acoustic phonon bunching
large acoustic-optical gaps

e.g., BP, BAs



Thermal Management for IC

J. Maire

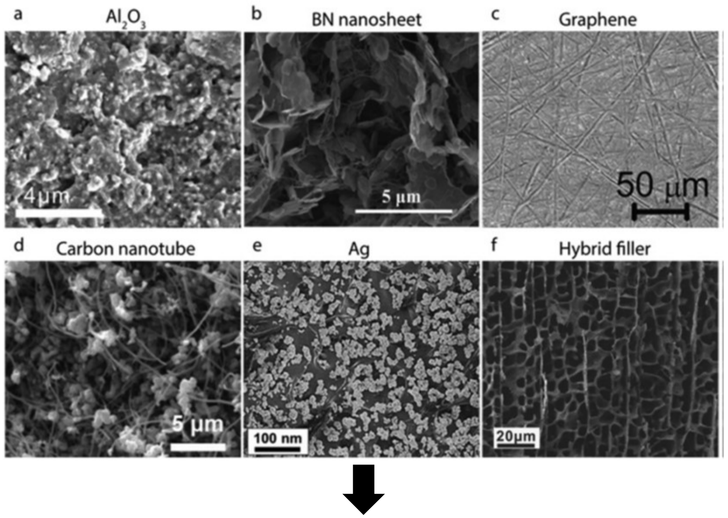
Techniques

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)

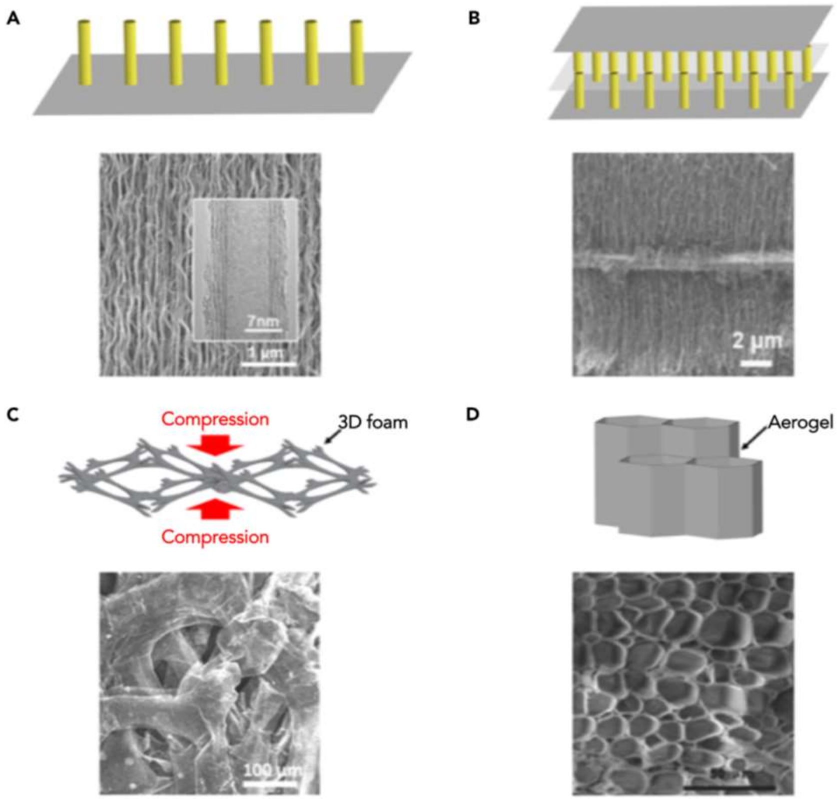


high κ with minimized filler loading

- 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

GDR NAnoMaterials for Energy applications

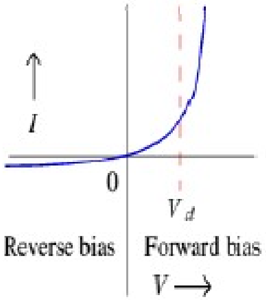
Thermotronics

P. Ben-Abdallah
Y. Ezzahri
K. Joulain

Historical breakthroughs in electronics

Diode

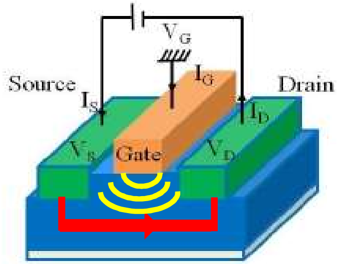
F. Braun
1874



- **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).*

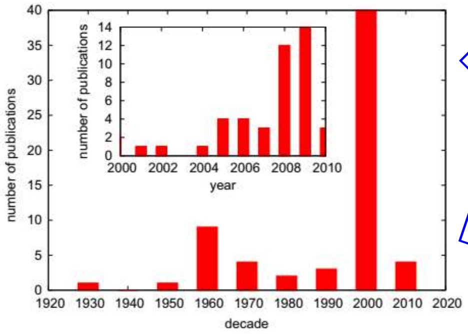


Fig. 1. Number of publications on thermal rectification per decade since 1936.

"1936: First experimental observation of thermal rectification"

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

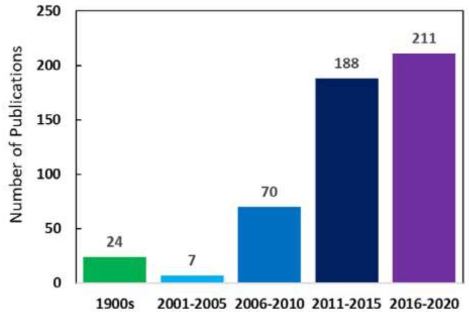


Fig. 2. Number of publications of thermal diode studies from the 1900s to present.

*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

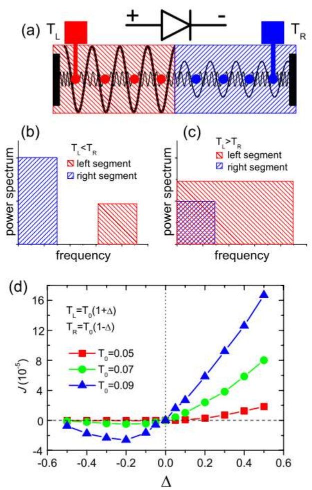
Different mechanisms

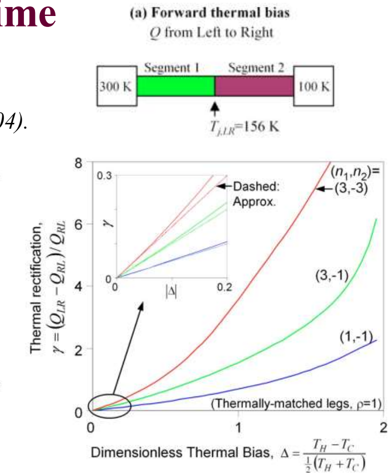
- **Conductive regime:** Asymmetric mismatch in phonon spectra (Nonlinear lattice coupled with harmonic spring) / Asymmetric Kaptiza resistance / Asymmetric temperature dependent thermal conductivity / Metal-insulator transition (hysteretic thermal behavior of Phase transition materials PTM)⟶ Phononics.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

Conductive regime

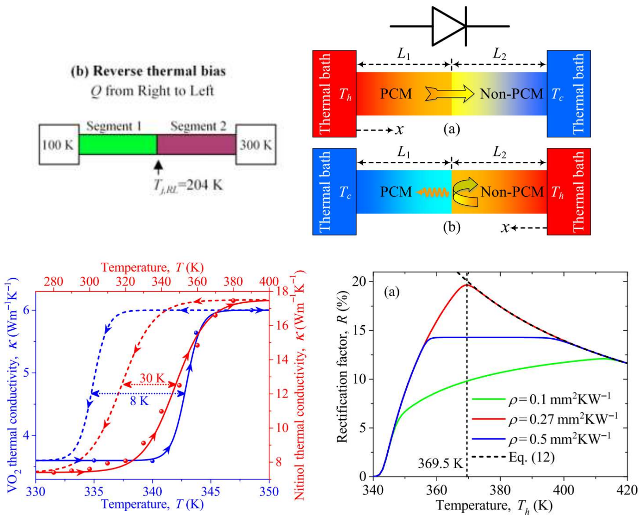
Theory

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





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



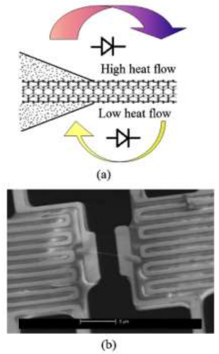
J. Ordonez-Miranda et al., JAP, **123**, 085102 (2018).

Rectification factor

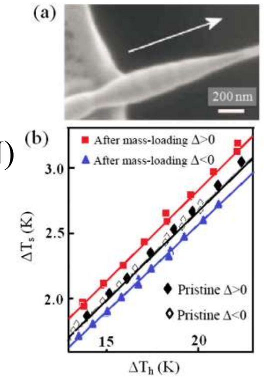
$$R=\frac{|\Phi_F-\Phi_R|}{Max\{\Phi_F,\Phi_R\}};\ \frac{|\Phi_F-\Phi_R|}{\Phi_{F,R}};\ \frac{|\Phi_F-\Phi_R|}{\Phi_F+\Phi_R};\ \frac{\Phi_F}{\Phi_R}$$

Experiment

C. W. Chang et al., Science, **314**, 1121 (2006).



Boron nitride (BN) nantube



Limitations:

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

GDR NAnoMaterials for Energy applications

Thermotronics

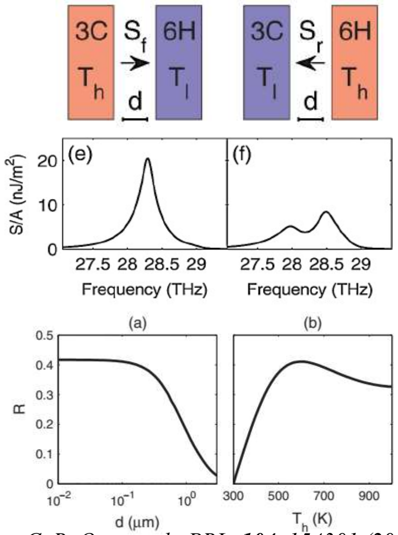
P. Ben-Abdallah
Y. Ezzahri
K. Joulain

Thermal rectifiers and thermal diodes

Radiative regime

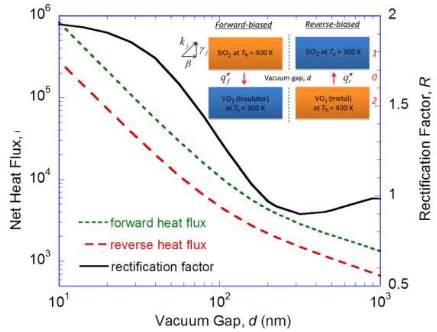
Theory

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



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

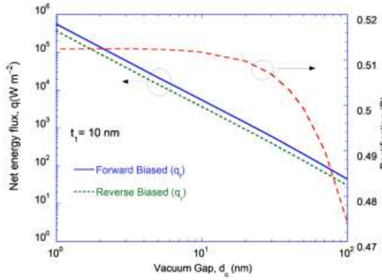
Thin film and bulk doped Si

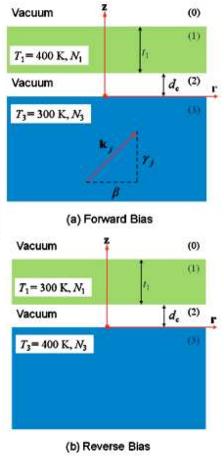


Y. Yang et al., APL, ***103****, 163101 (2013).*

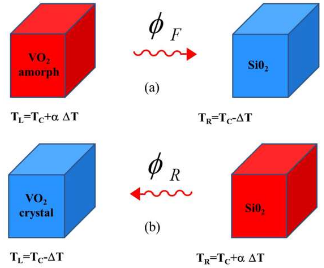
Near Field

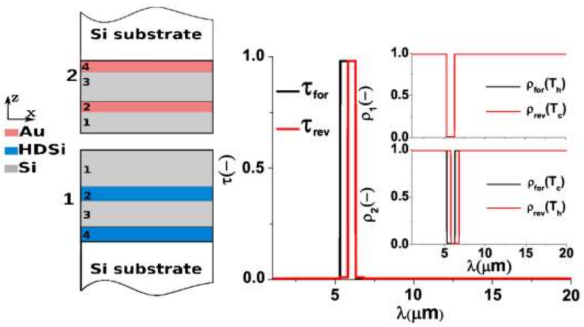
S. Basu and M Francoeur, APL, ***98****, 113106 (2011).*





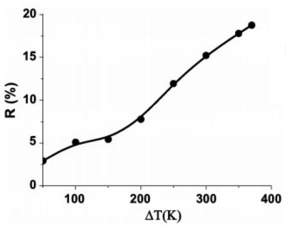
Near Field

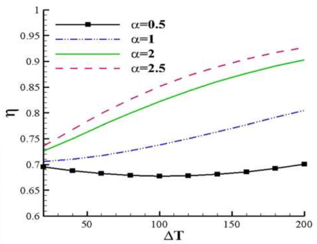




E. Nefzaoui et al., AO, ***53****, 3479 (2014).*

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





Far Field

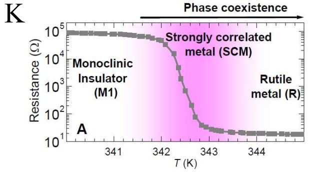
P. Ben-Abdallah and S. A. Biehs, APL, ***103****, 191907 (2013).*

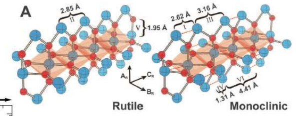
Experiment

➤Using phase change (transition) materials or superconductors

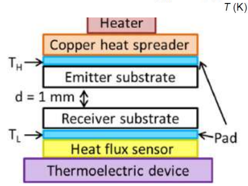
Mott transition at 340 K

VO_2

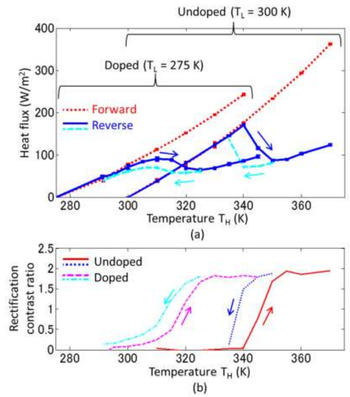




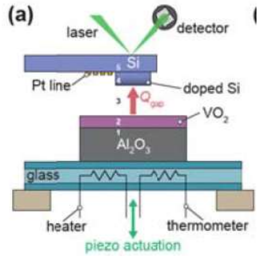
Far Field

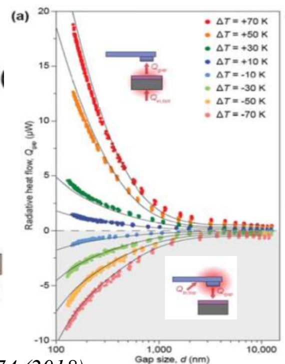


K. Ito et al., APL, ***105****, 253503 (2014).*

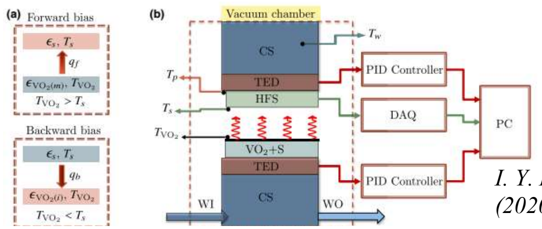


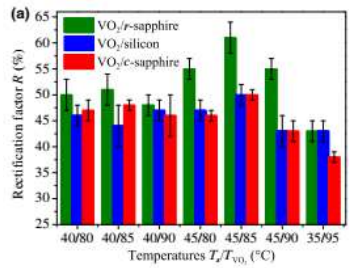
Near Field





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





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

NAME

GDR NAnoMaterials for Energy applications

Thermotronics

Thermal transistors

Conductive regime

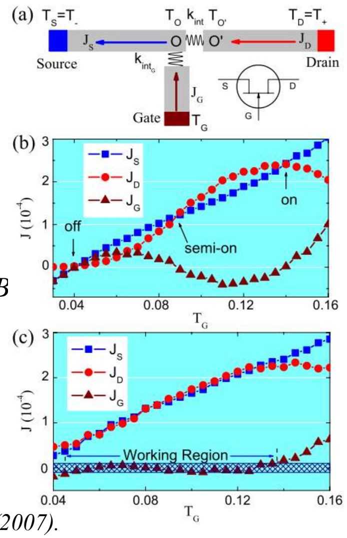
B. Li et al., APL, **88**, 143501 (2006).

"Thermal transistor effect ↔ negative differential thermal resistance"

Amplification factor

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

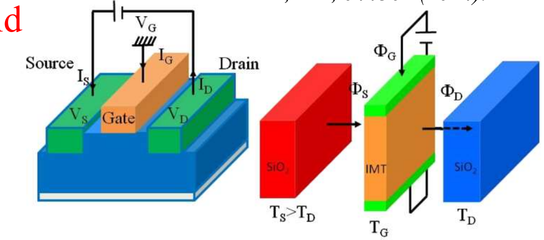
N. Li, J. Ren, L. Wang, G. Zhang, P. Hänggi and B Li, Review of Modern Physics, **84**, 1045 (2012).

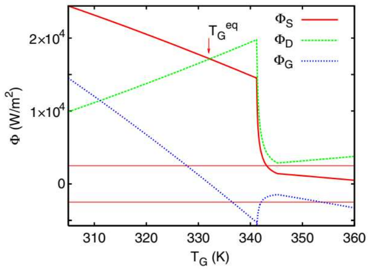


Radiative regime

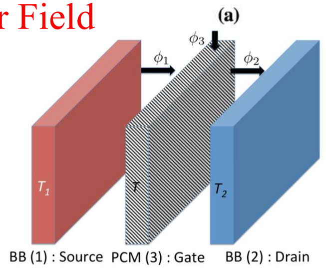
P. Ben-Abdallah and S. A. Biehs, PRL, **112**, 044301 (2014).

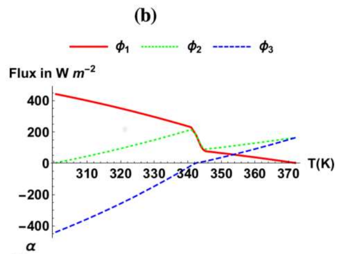
Near Field

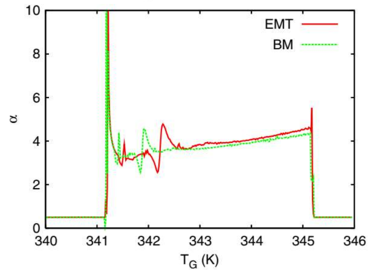


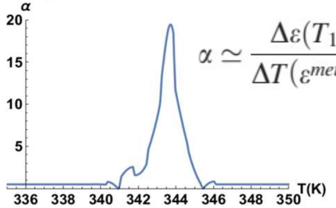


Far Field









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

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

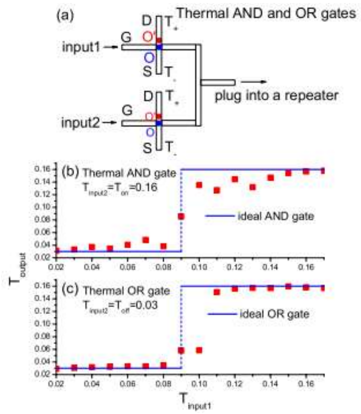
Operating modes:

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

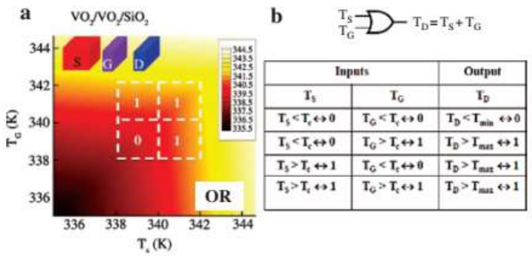
Thermal logical gates and memories

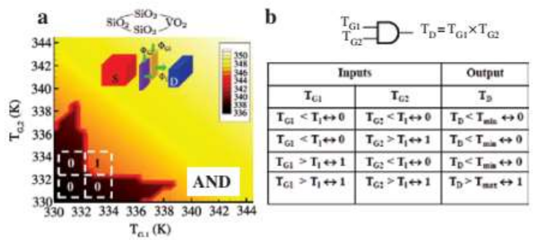
Conductive regime

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



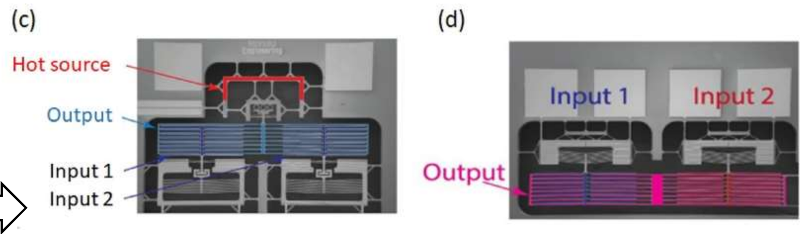
Radiative regime





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

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



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

NAME
GDR NAnoMaterials for Energy applications

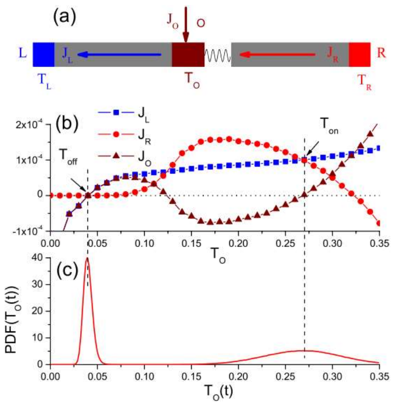
Thermotronics

P. Ben-Abdallah
Y. Ezzahri
K. Joulain

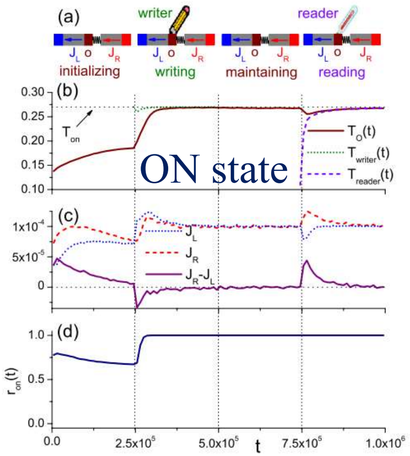
Thermal logical gates and memories

Conductive regime

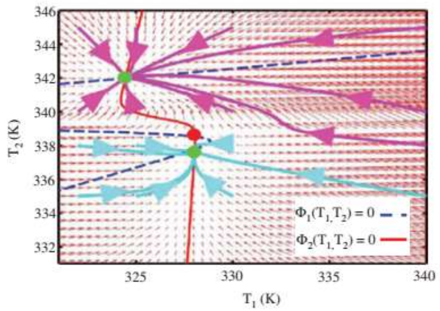
Theory

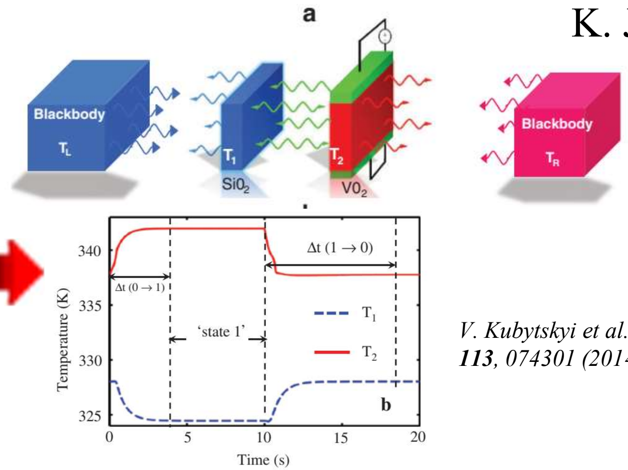


L. Wang and B. Li, PRL, **101**, 267203 (2008).



Radiative regime

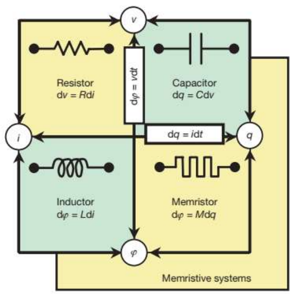




V. Kubytskyi et al., PRL, **113**, 074301 (2014).

Thermal memristor

Memristor = Memory resistor



Chua's Memristor

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

$$\frac{dw}{dt} = i$$

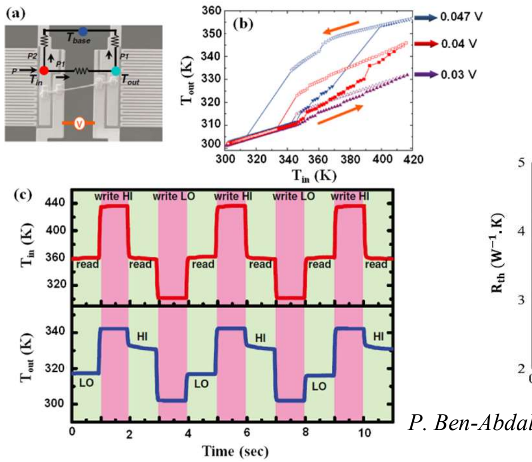
Memristive system

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

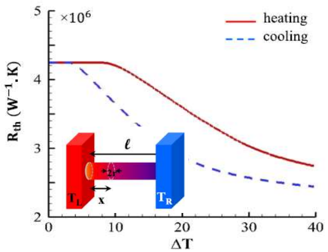
$$\frac{dw}{dt} = f(w,i)$$

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

Experiment

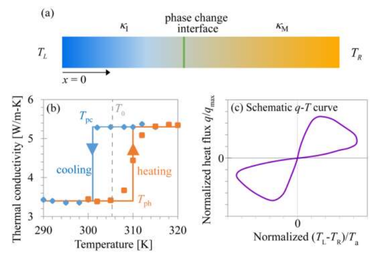


R. Xie et al., Adv. Funct. Mater, **21**, 1602 (2011).



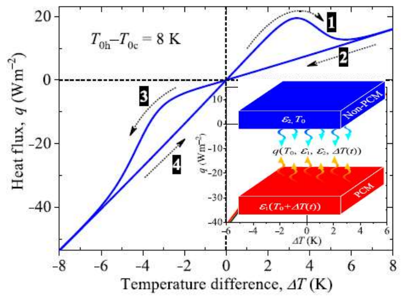
P. Ben-Abdallah, AIP Advances, 7, 065002 (2017).

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).

GDR NAnoMaterials for Energy applications

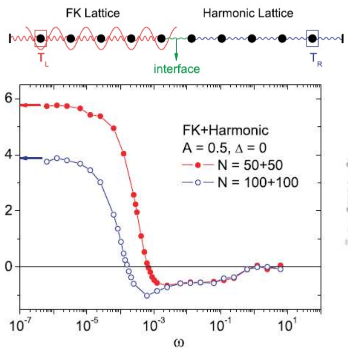
Thermotronics

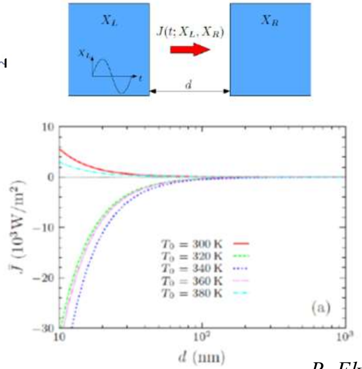
P. Ben-Abdallah
Y. Ezzahri
K. Joulain

Active control of heat flux

Shuttling and ratcheting

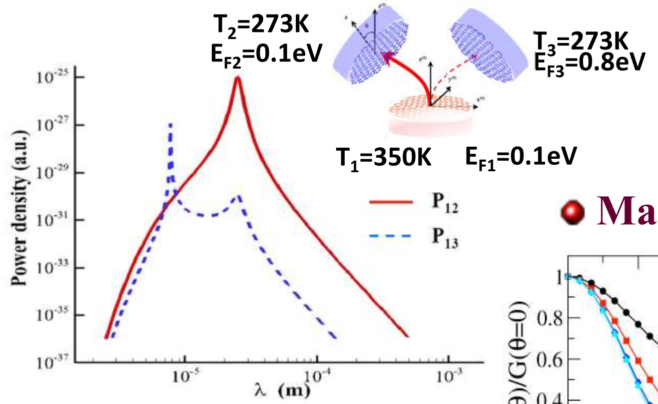
Pumping heat against the thermal bias





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).*

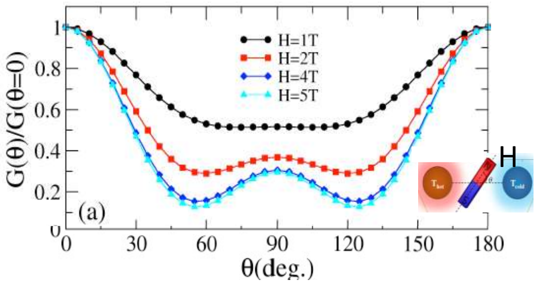
Heat splitting



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

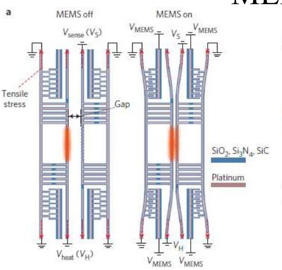
R. Ekeroth et al. ACS Photonics, ***5****, 705, (2018).*
I. Latella et al. PRL ***118****, 173902 (2017).*

Magnetic control

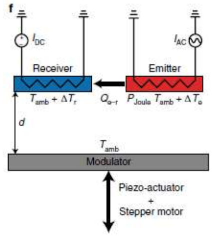


Mechanical control

MEMS/NEMS

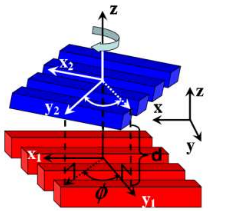


R. St. Gelais et al., Nature Nanon ***11****, 515 (2016).*



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

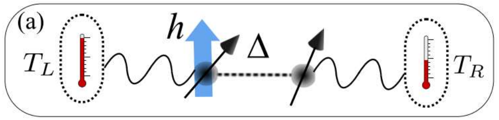
Gratings rotation



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

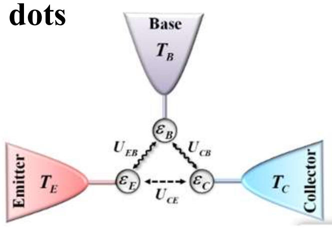
How about the quantum regime?

Thermal diode



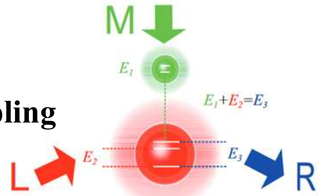
T. Werlang et al., PRE, ***89****, 062109 (2014).*

Using Colomb-coupled quantum dots



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

Using Qubit-Qutrit coupling

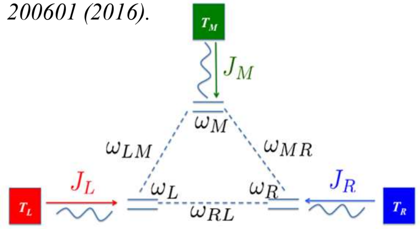


B. Guo et al., PRE, ***98****, 022118 (2018).*

Thermal transistor

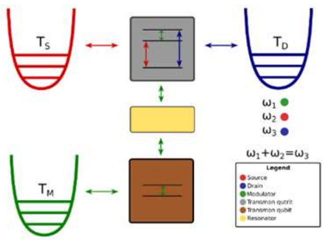
Using Qubits

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

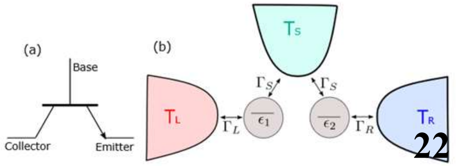


Using Superconductors

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



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



Thermotronics

NAMe

GDR NAnoMaterials for Energy applications

P. Ben-Abdallah
Y. Ezzahri
K. Joulain

Challenges and perspectives

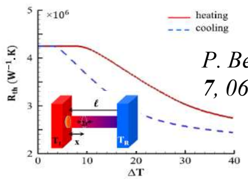
Challenges

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

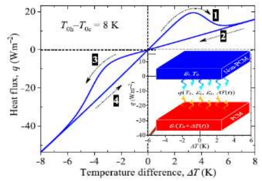
Perspectives

- **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

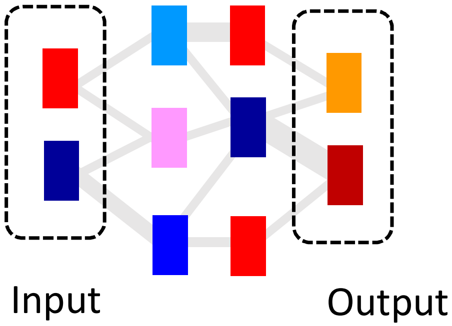


P. Ben-Abdallah, AIP Advances 7, 065002 (2017).



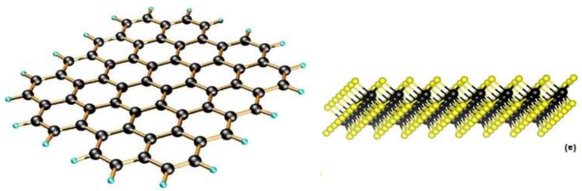
*J. Ordonnez-Miranda et al., PRL **123**, 025901 (2019).*

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



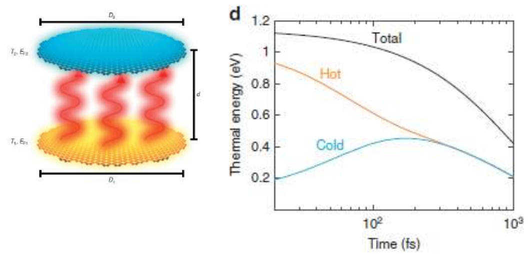
Neuromorphic computing

Two dimensional materials



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

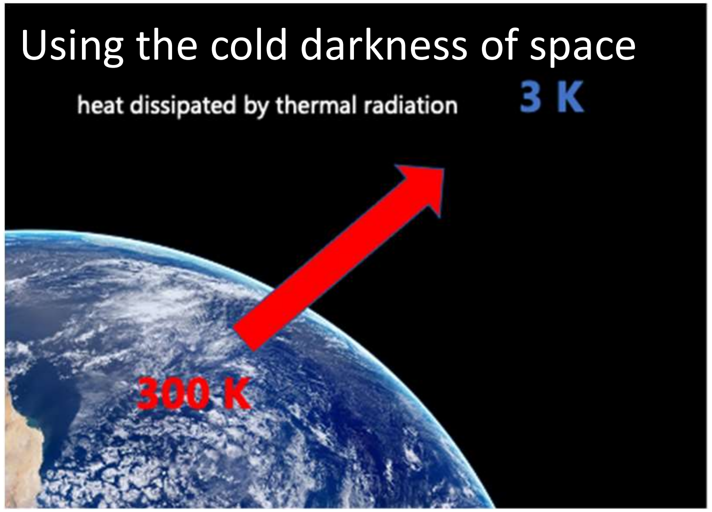
Systems far from equilibrium



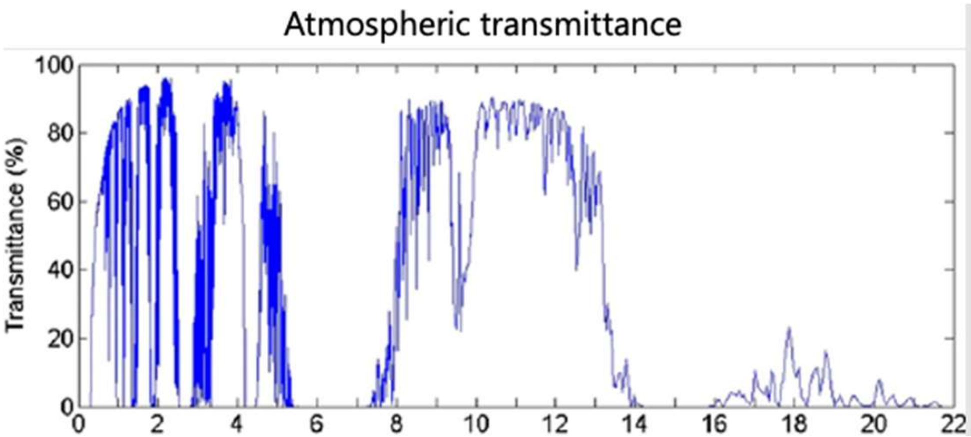
- **Electrons and phonons at different temperatures.**
- **Heat flux control at pico and subpicosecond scale…**

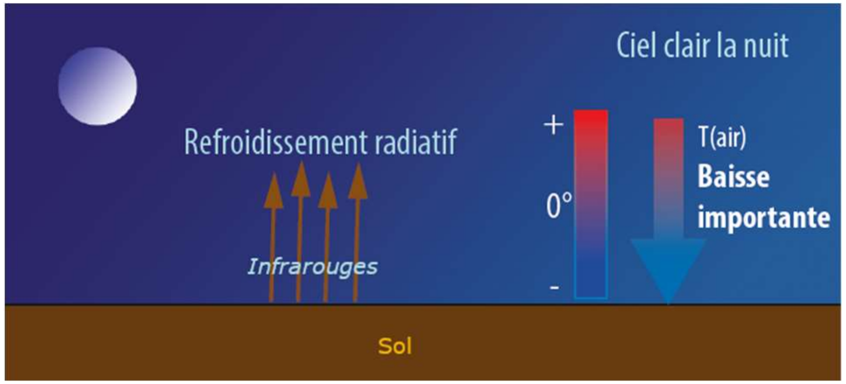
Radiative cooling

J. Drévillon



at night, objects and the ground cool by radiation, become colder than ambiant

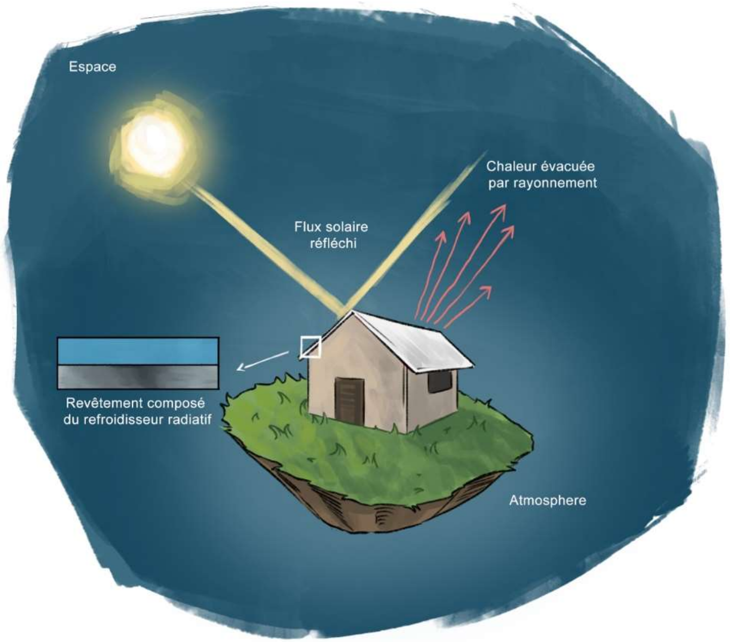


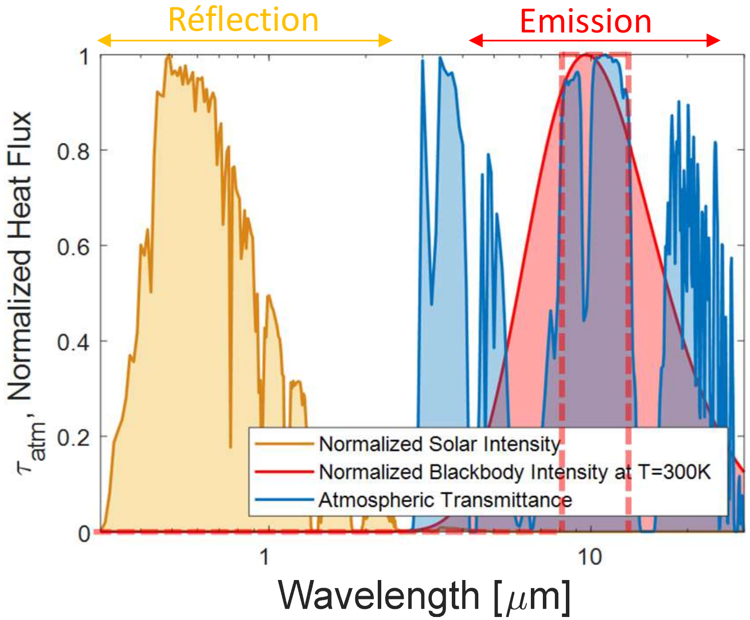


N A M e

Radiative cooling

J. Drévillon

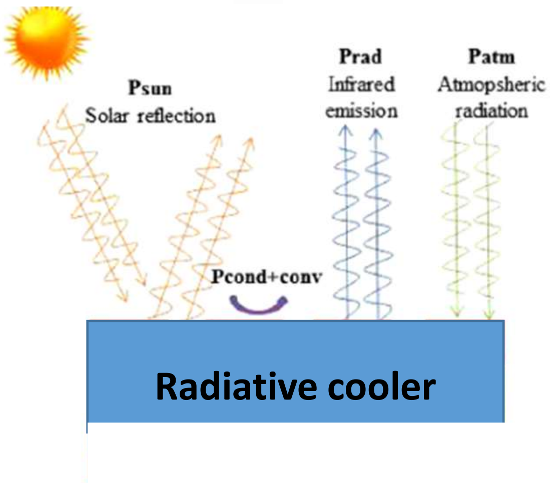




Cooling of the structure (T = 300 K) by direct heat transfer with space (T = 3K).

No energy to provide for cooling

Design of coatings reflecting in the solar radiation spectrum and highly emitting in the IR



➡ Control and optimization of radiative properties over a broad spectrum

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

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

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

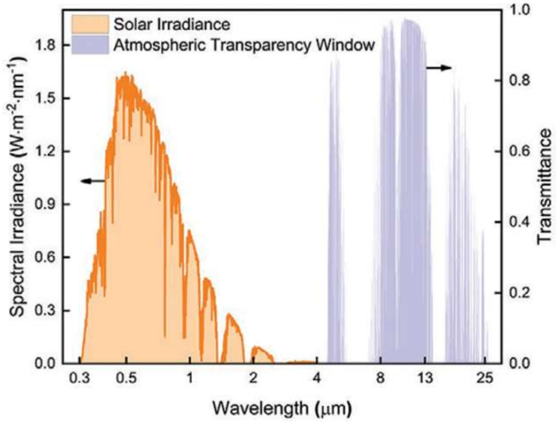
$$P_{\mathrm{sun}} = A\int_0^\infty \mathrm{d}\lambda\varepsilon(\lambda,0) I_{\mathrm{AM\,sw1.5}}(\lambda)$$

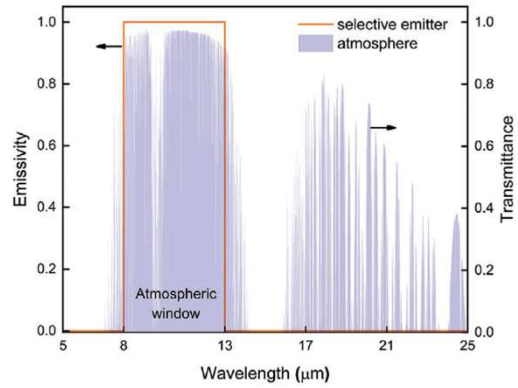
Radiative cooling

J. Drévillon

GDR NAnoMaterials for Energy applications

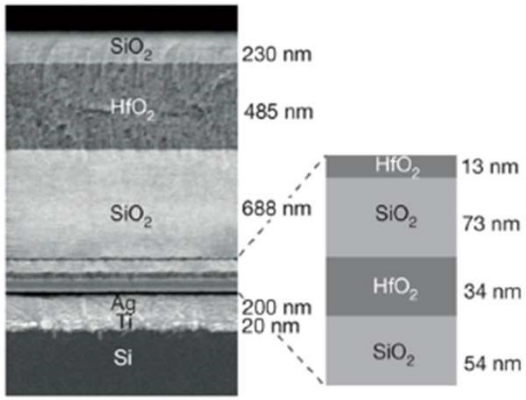
- How to minimize the absorption of solar radiation?
- How to optimize the emission of heat by radiation in the sky window?

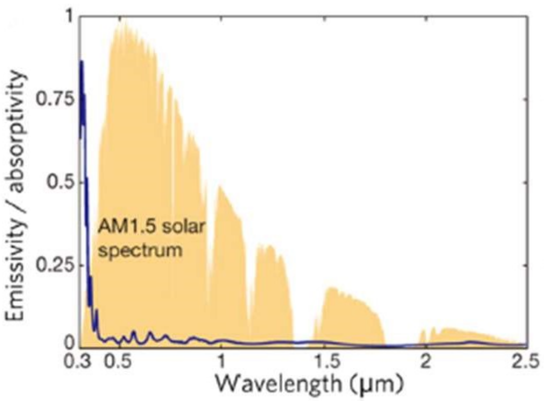


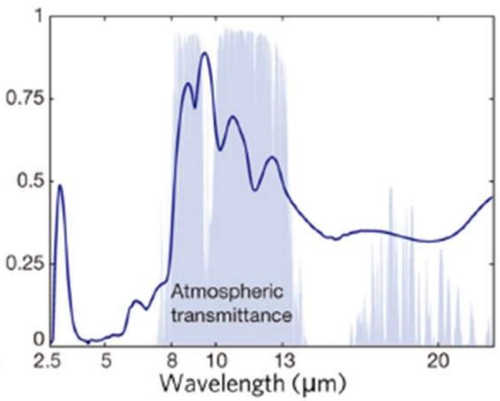


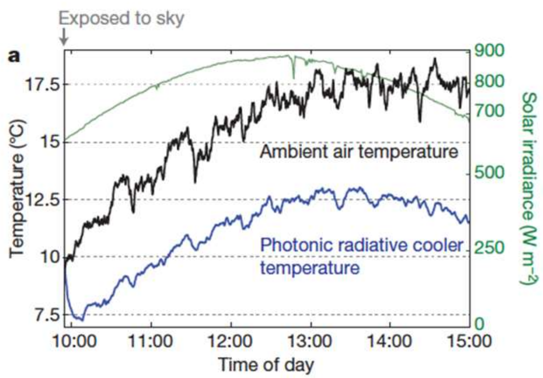
Different approaches

Nanophotonic approach: thin films stack









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

Always composed of two main parts aiming to
. increase the reflectivity of the structure in the short wavelength range (0,3-2,5 μm) ->solar spectrum
. Enhance the emissivity of the structure in the atmospheric window (8-13 μm)

NAMe GDR NAnoMe

Radiative cooling

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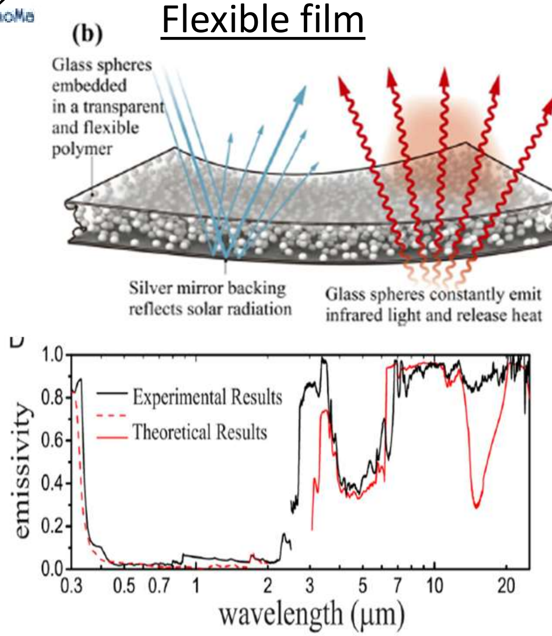
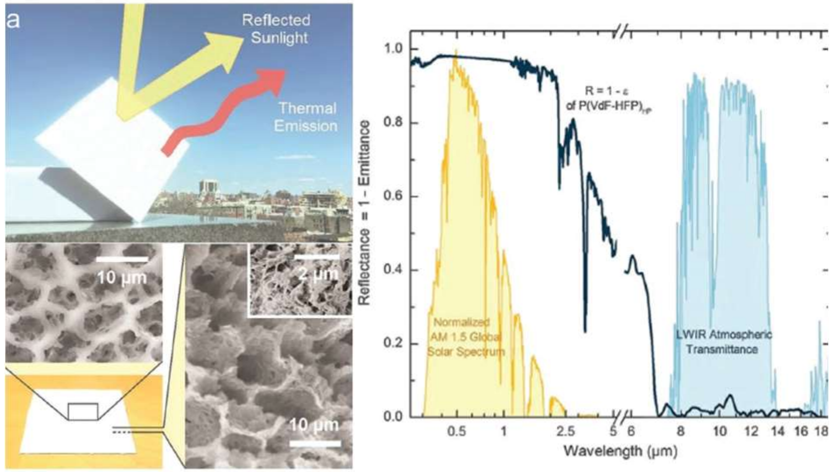
Flexible film



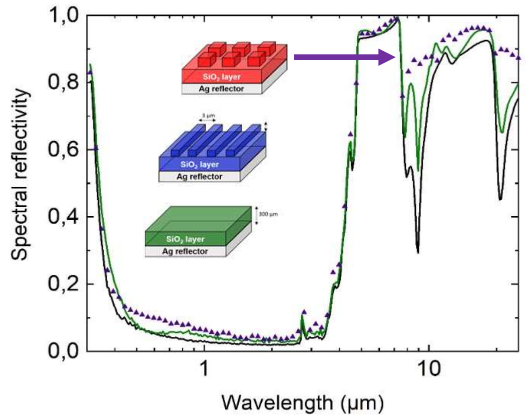
Zhai Y, *et al.*, *Science, 2017*

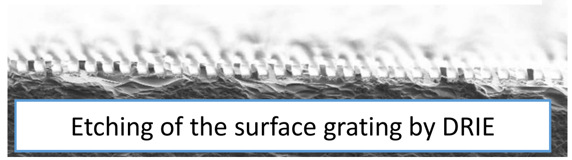
Nano/micro Porous Polymer



J. Mandal, *et al.*, Science, 2018

Patterned surface

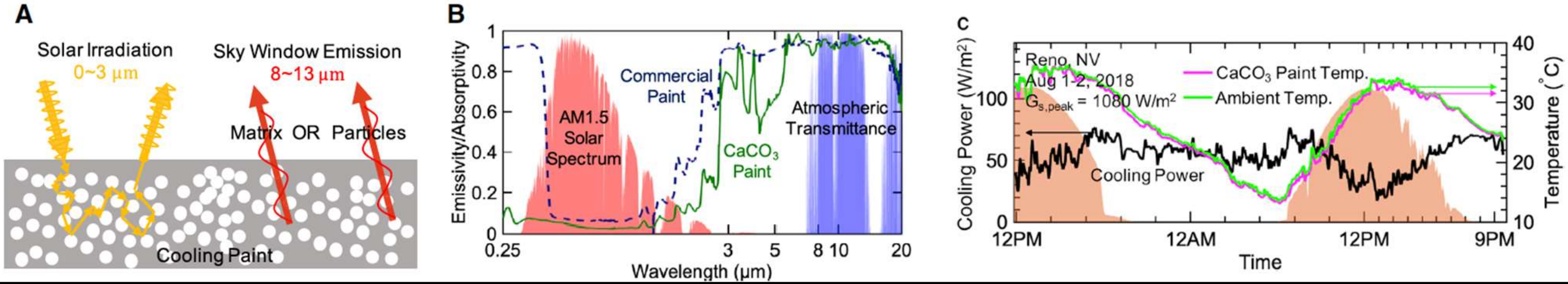




Blandre E. *et al*, Optics Express,2020

Paints

Xiangyu Li, *et al.,* Cell Reports Physical Science, 2020

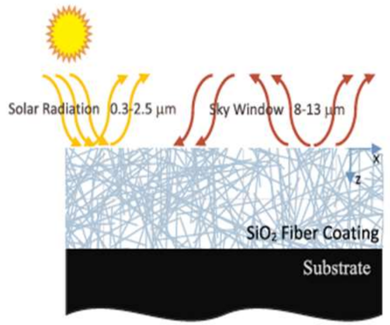


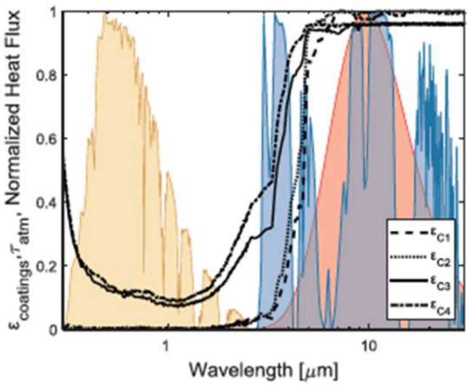
Radiative cooling

J. Drévillon
E. Nefzaoui

Different approaches

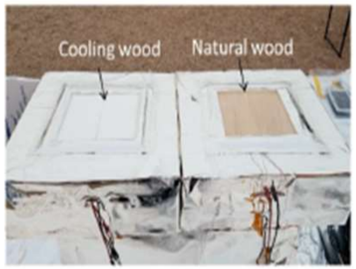
SiO$_2$ nanofibers

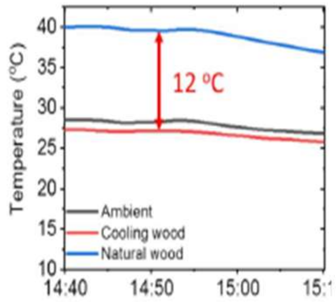


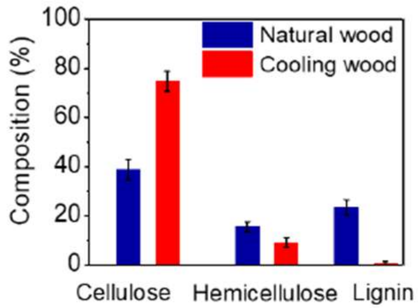


R. Yalçın *et al.*, Solar Energy Materials and Solar Cells,2020

Delignified wood

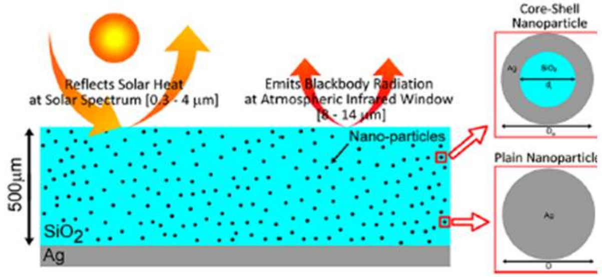


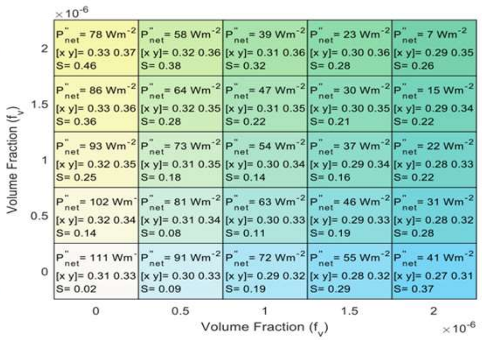




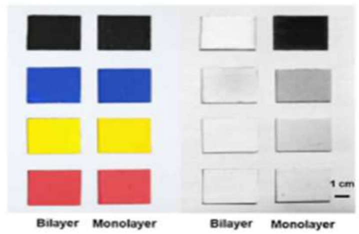
T. Li *et al.*, Science, 364, 6442 (2019).

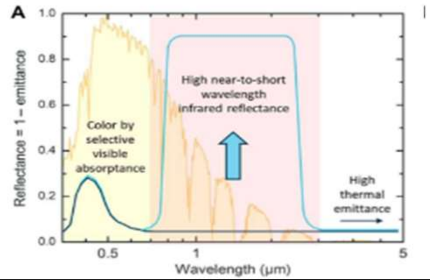
Colored PDRC





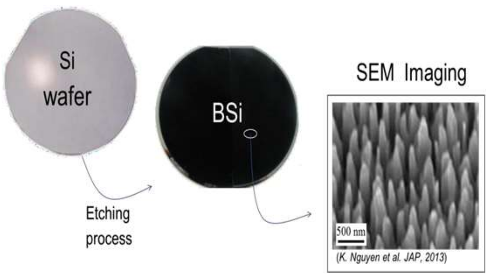
R. Yalçın et al., ACS Photonics, 7, 1312 (2020).

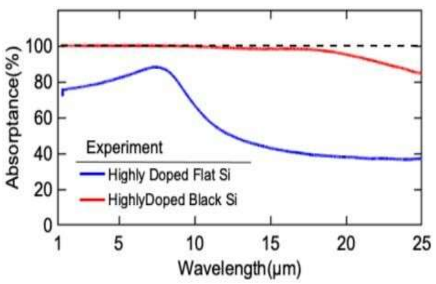




*Y. Chen et al., Science Advances, **6**, 1 (2020).*

Black silicon (Bsi)





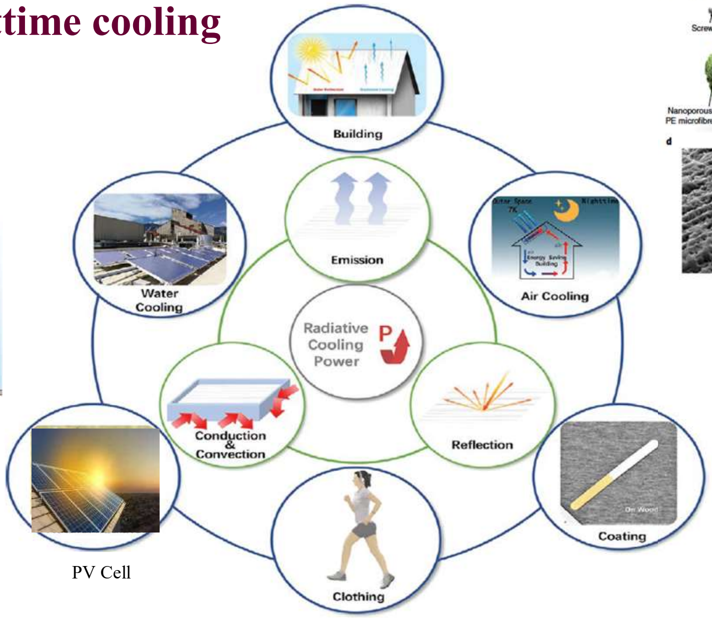
Radiative cooling

J. Drévillon
M. Amara
Y. Ezzahri

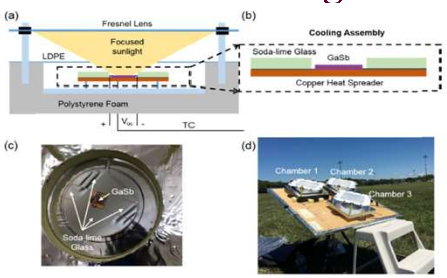
GDR NAnoMaterials for Energy applications

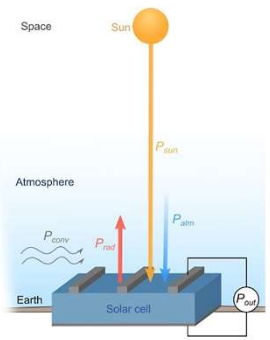
Applications

- **Multiple potential applications: daytime and nighttime cooling**



- **PV/TPV cooling**



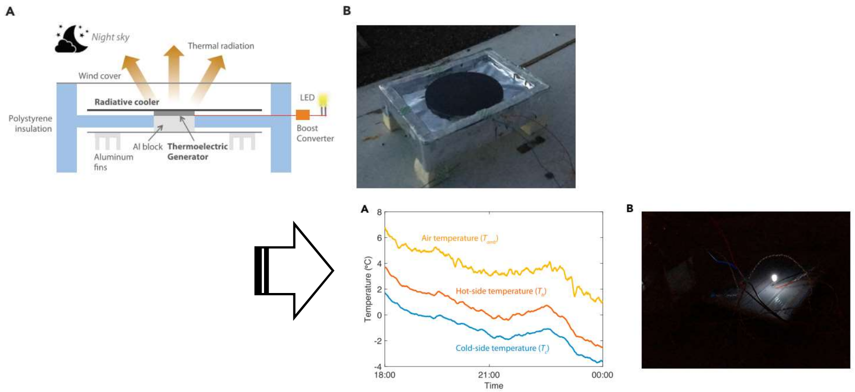


Z. ZHOU et al., Optics Express, 27, A404 (2019).

- **Enhancing thermoelectric generation**

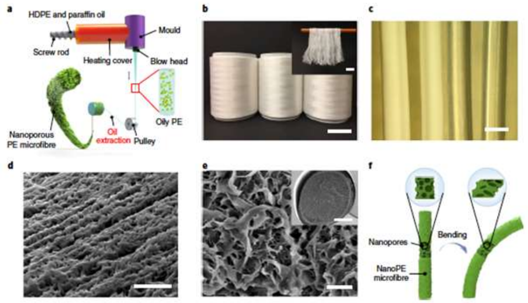
A. P. Raman et al., Joule, 3, 1 (2019).

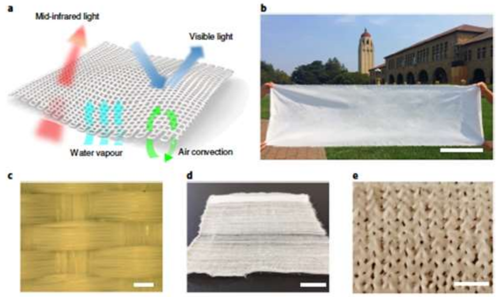
Generating light from darkness!



- **Human body cooling**

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

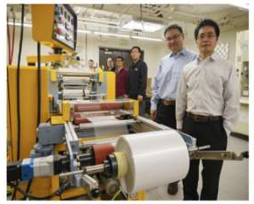


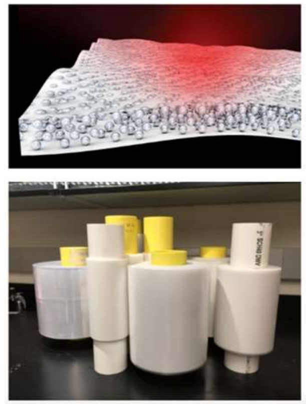


- **Start-UP**
  - **Sky-cool**

  - **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!