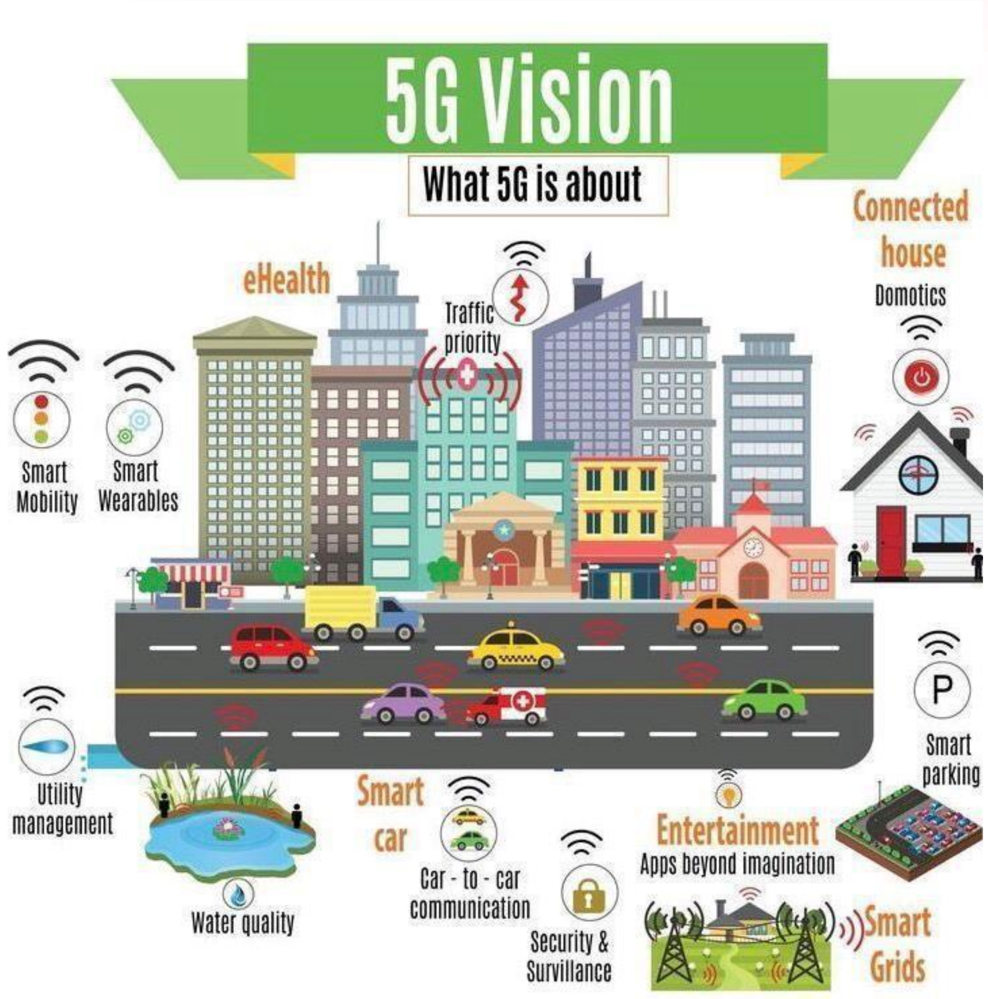
Thermal management for 5G

Jérémie Maire

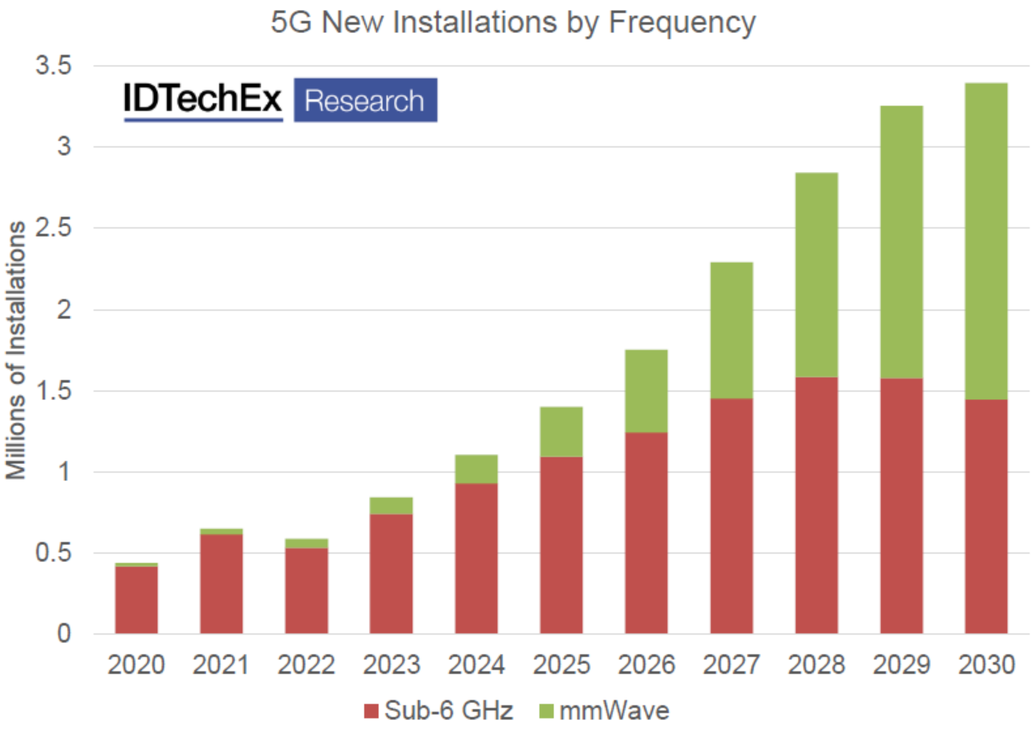
Based on the report from IdTechEx Research

Dr James Edmondson, Dr Luyun Jiang & Dr Khasha Ghaffarzadeh

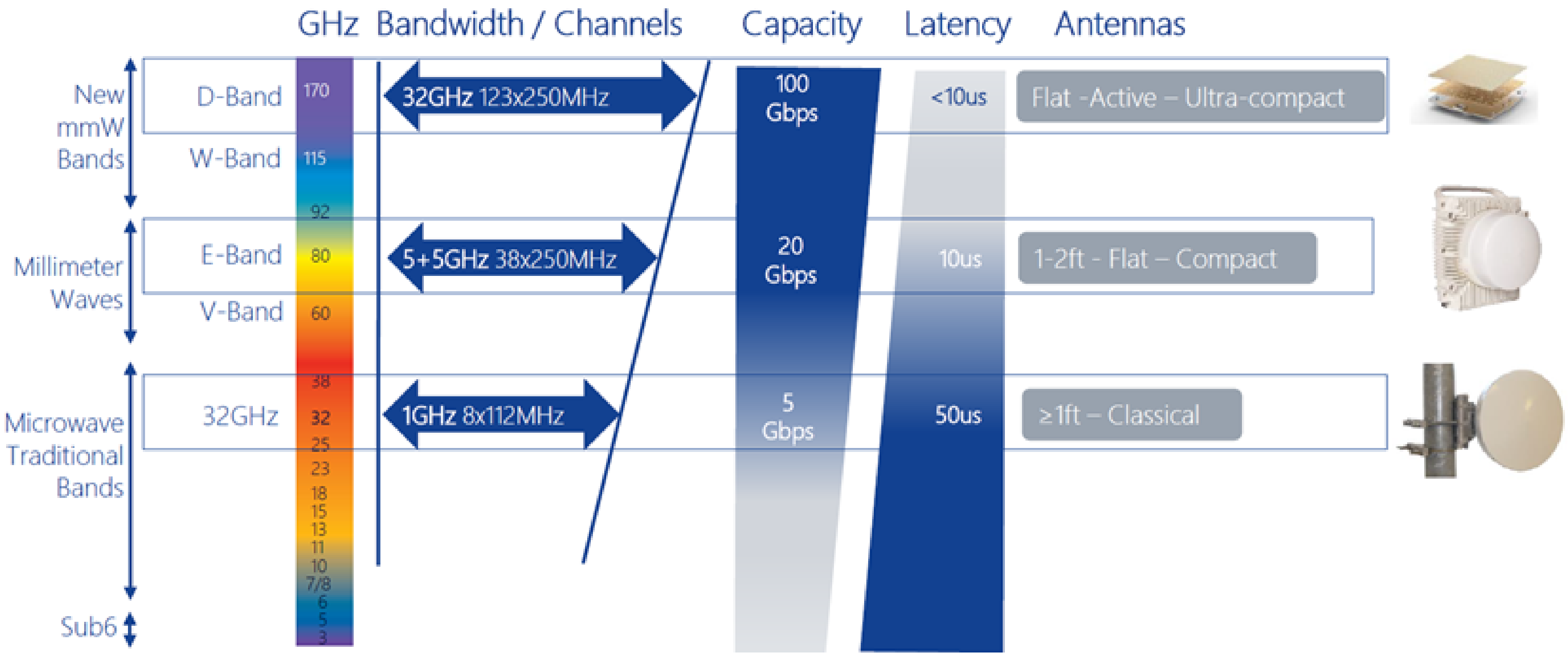
5G: What and Why ?



« 5G is a collection of optimised and updated mobile communication technologies and new characters coming from the **change of frequency** (mainly two high frequencies, **sub-6GHz or 20-40 GHz**) and **larger bandwidth**. »



5G: Differences with 4G

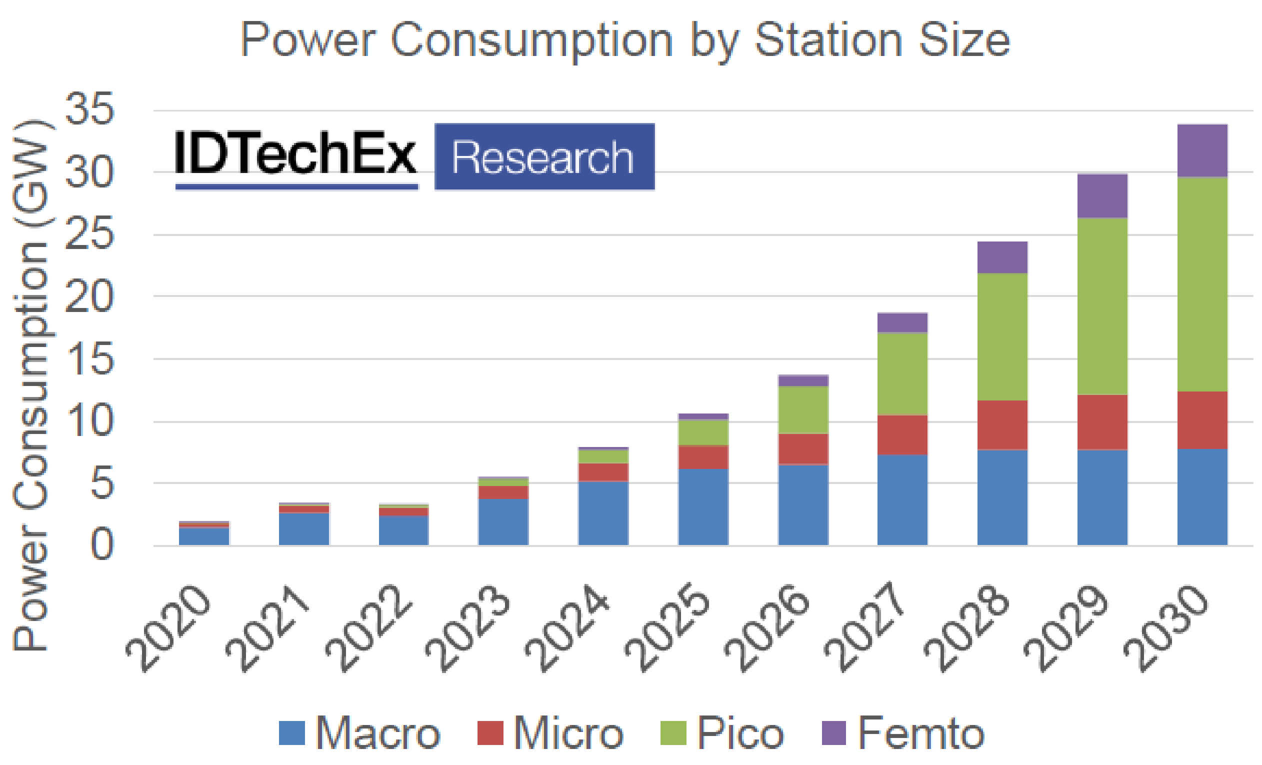


- Wider bandwidth
- Higher capacity
- Lower latency.
- Smaller antennas
  → high density antennas arrays.

GaN or GaAs on the Antenna side
Si-based technologies on the device side

Power consumption forecast 5G

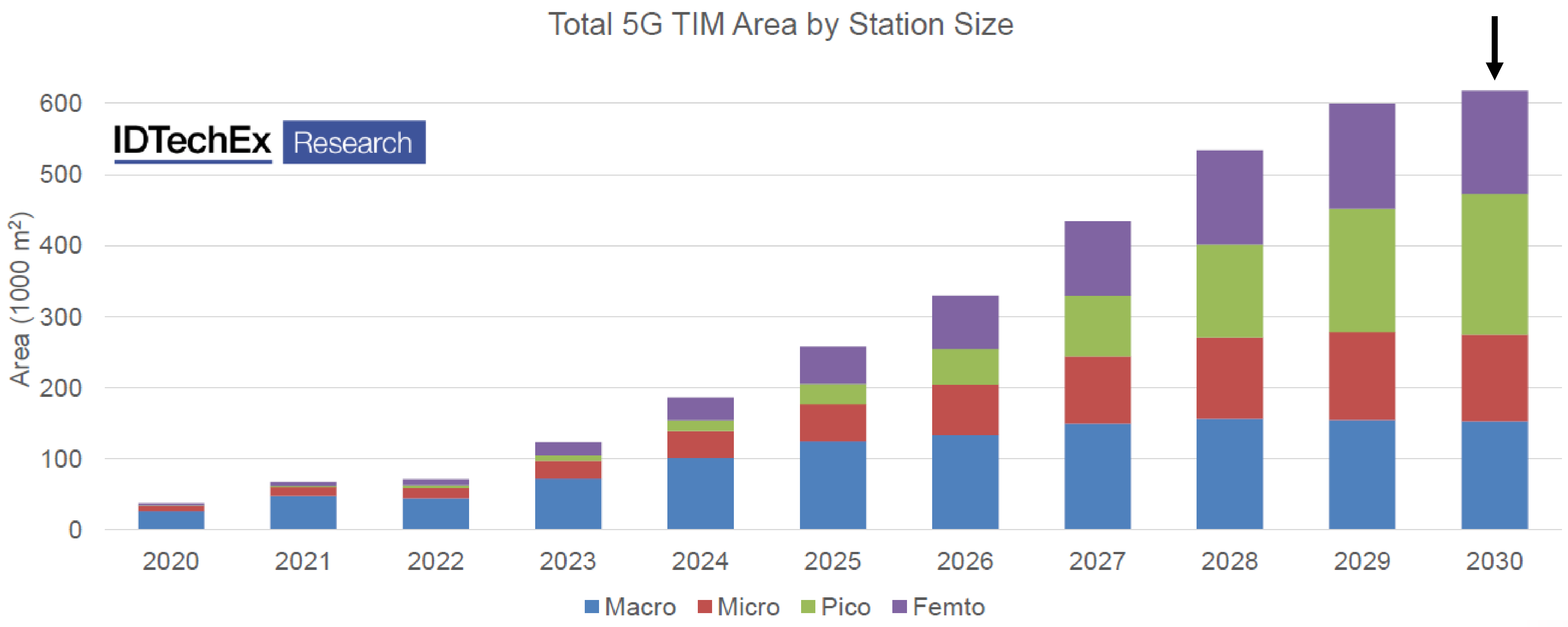
Increase in power consumption for 5G installations by more than a factor 10 in 10 years



Total TIM requirements estimates for 5G

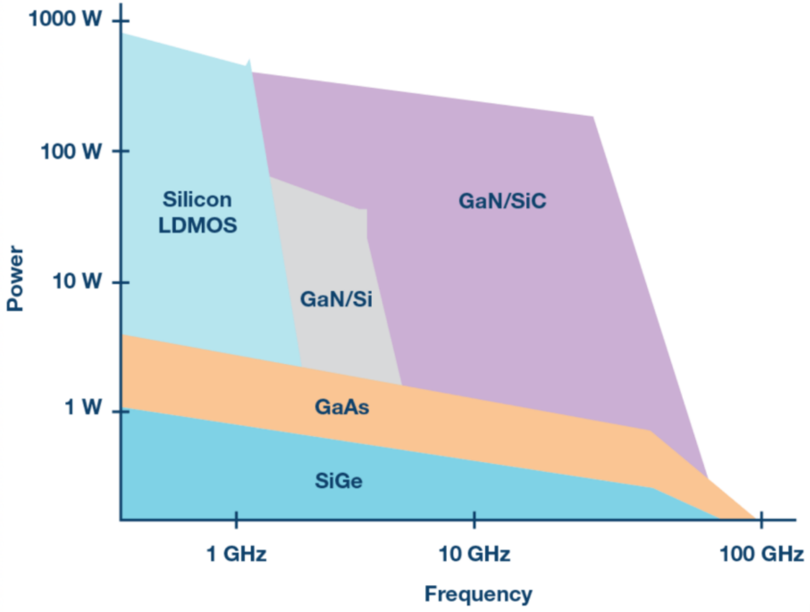
TIM = Thermal Interface Material

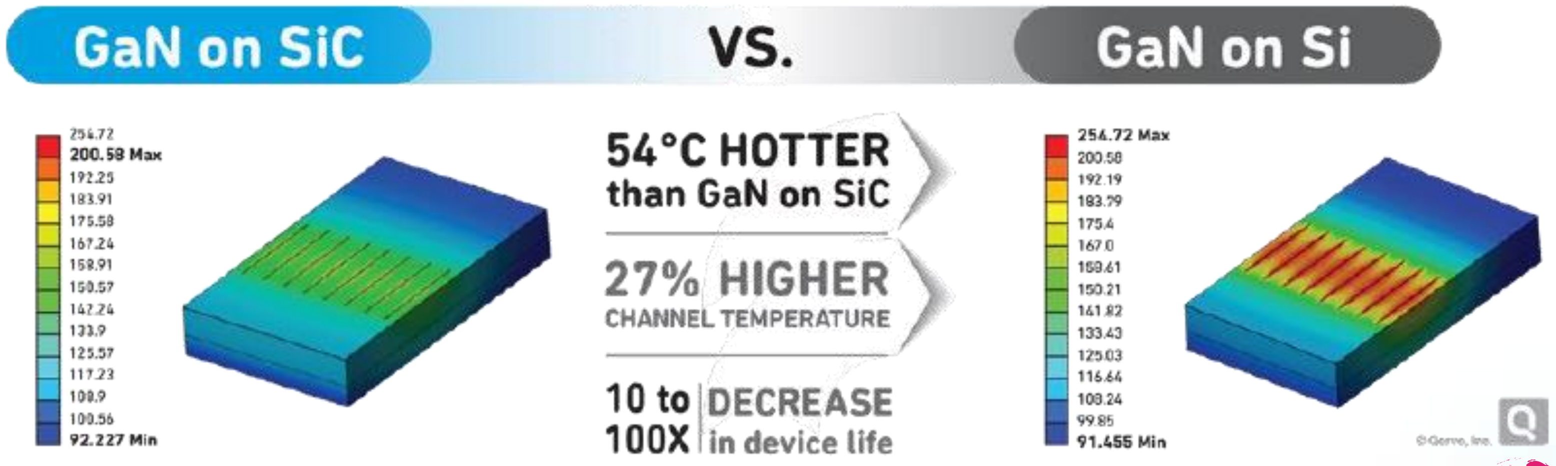
= 1.5 x Vatican



Thermal management for 5G

- mmWave → higher clock speed in device chips → produces the most heat in devices. Plus, large increase in the number of individual small cells.
- Central offices are also likely to change and move to resembling data centres, which may present new thermal challenges to manage these systems.
- The need for effective thermal management of 5G smartphones has been highlighted with public tests of new devices where the phone has switched off or dropped to 4G in order to avoid overheating.





Current/future cooling strategies

Mainly passive cooling strategies

Increasing use of heat pipes and vapour chambers in the near future → système

Improvements in the overall thermal design → Système / Puce

Improvements in materials (e.g. use of graphene) → Matériaux

Complement with active cooling strategies such as thermoelectric cooling

high performance at the cost of increased energy consumption


Chris Martin, Techadvisor

Thermal management for mobile devices

5G: Increased heat load

Sub-6 GHz + mm-wave (~30 GHz)

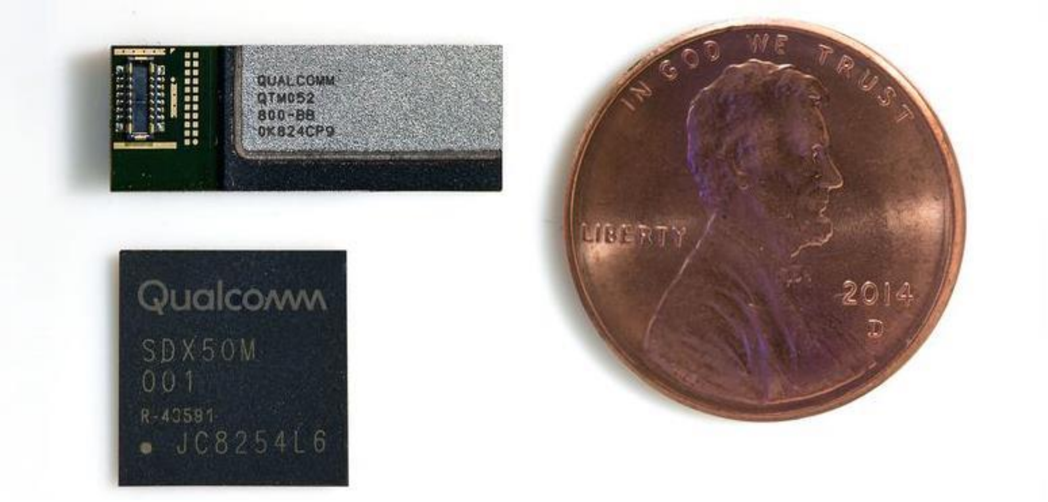
↓

Increased heat dissipation leads to thermal throttling

Cancelled Apple – Intel collaboration

↓

Not able to overcome heat dissipation and battery life chllenges



Qualcomm QTM052 5G antenna unit (top) along with the X50 5G modem (bottom)

Thermal throttling

Existing strategies to circumvent heating:

Qualcomm's 5G system drops down to 4G when the ambient temperature exceeds 30 °C

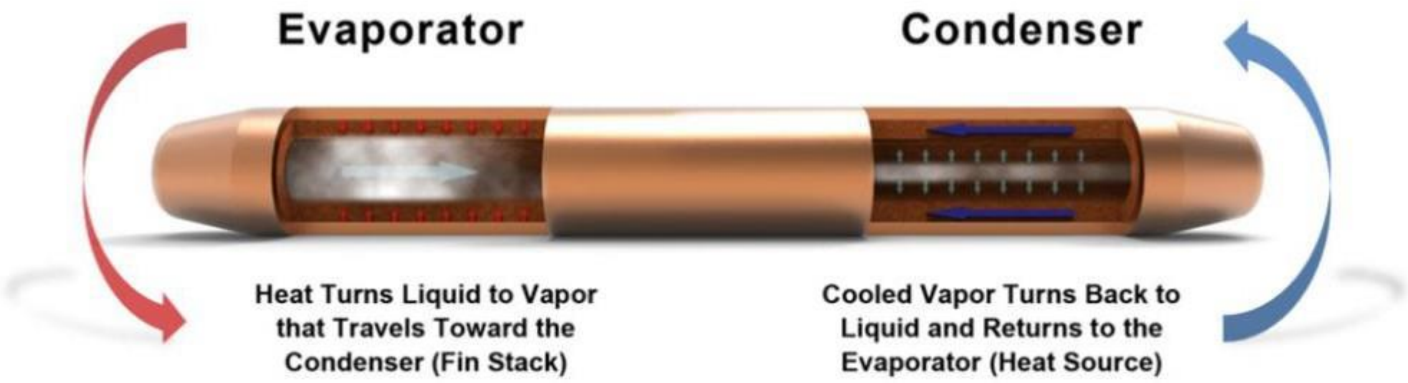
Different throttling strategies:

- **Temperature scheduling**: slow down processes creating the most heat
- **Thermal herding**: network traffic is distributed throughout the chip to avoid specific hotspots
- **Clock gating**: stop global CPU usage for microseconds at a time
- **Dynamic voltage and frequency scaling** to balance performance and energy consumption
- **Activity migration**: processes are run on spare, colder regions of the chip.

Thermal throttling

<u>Existing strategies to circumvent heating:</u>

- **Heat sinks** → increase surface area for convection.
- **Heat spreaders**: flat material with a high thermal conductivity to spread heat to the casing or chassis
- **Cold plates**: active cooling but added weight, complexity and size.
  Graphene heat spreaders with thermoelectric effect to provide active cooling.
- **Heat pipes and vapor chambers**: on the rise in 5G smartphones

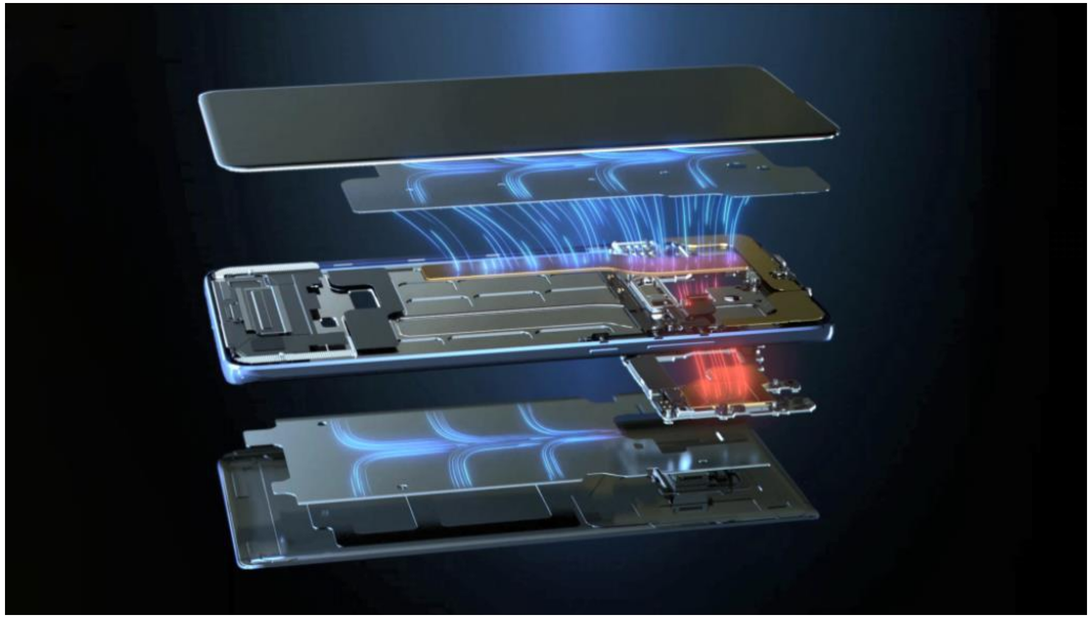


AIP Conference Proceedings 1745, 020020 (2016)

Recent commercial cooling solutions

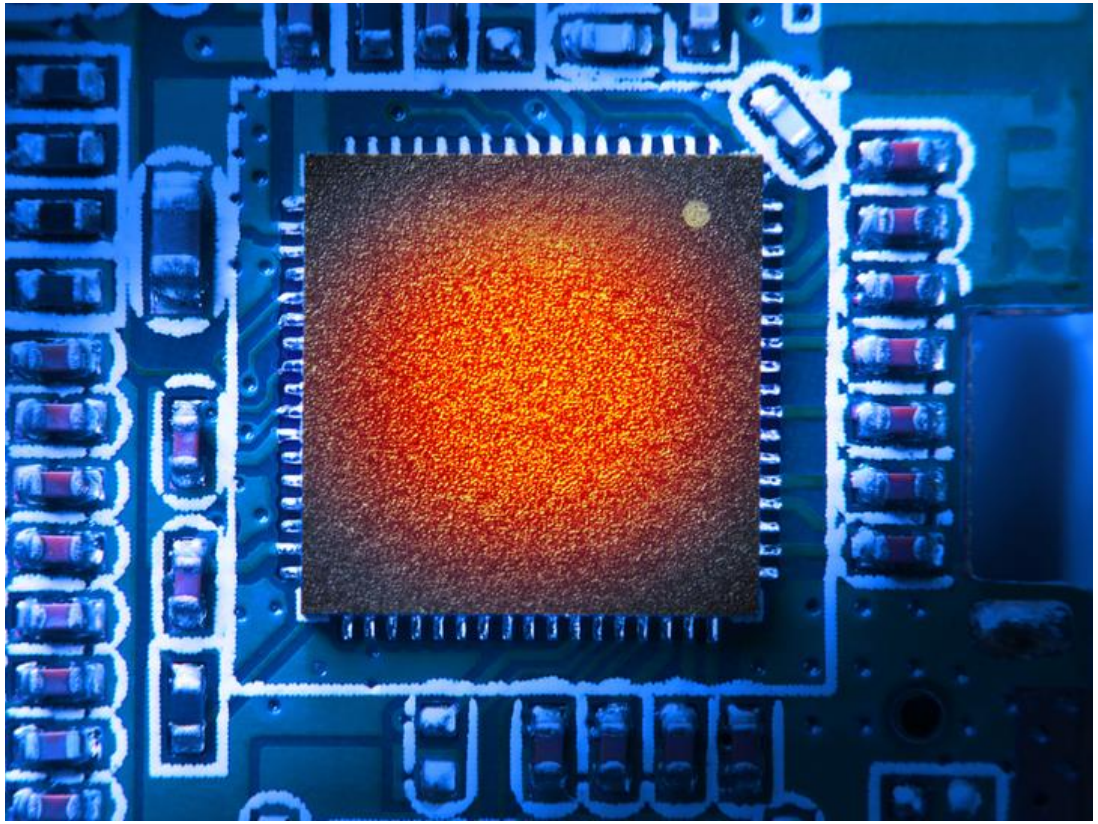
Examples of an hybrid cooling solution

Source: Samsung



Vapour chamber with graphene layer above

Source: pcmag



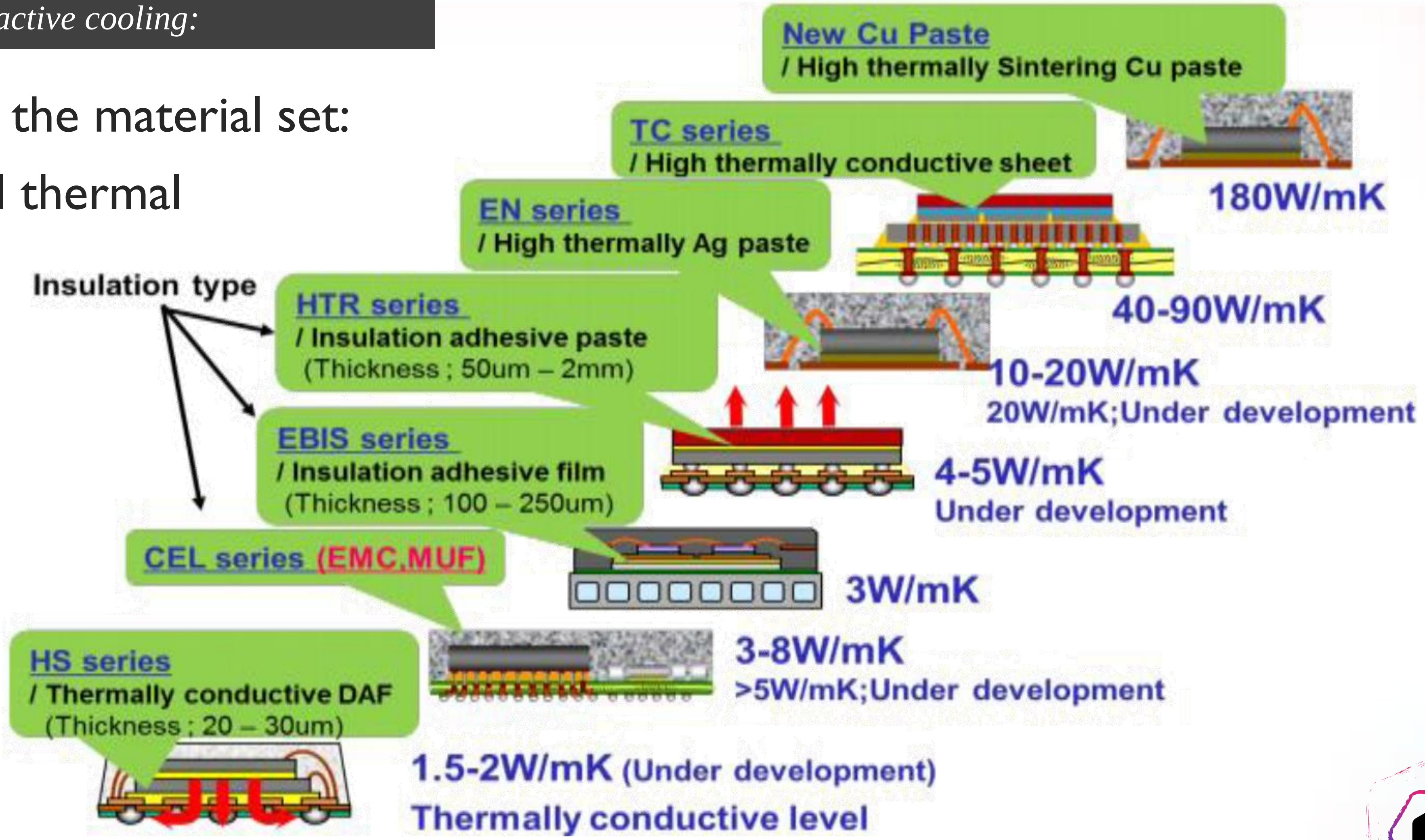
In-package heat dissipation

Thermally relevant package levels

In the absence of active cooling:

Heat dissipation across the material set:

Common materials and thermal conductivities

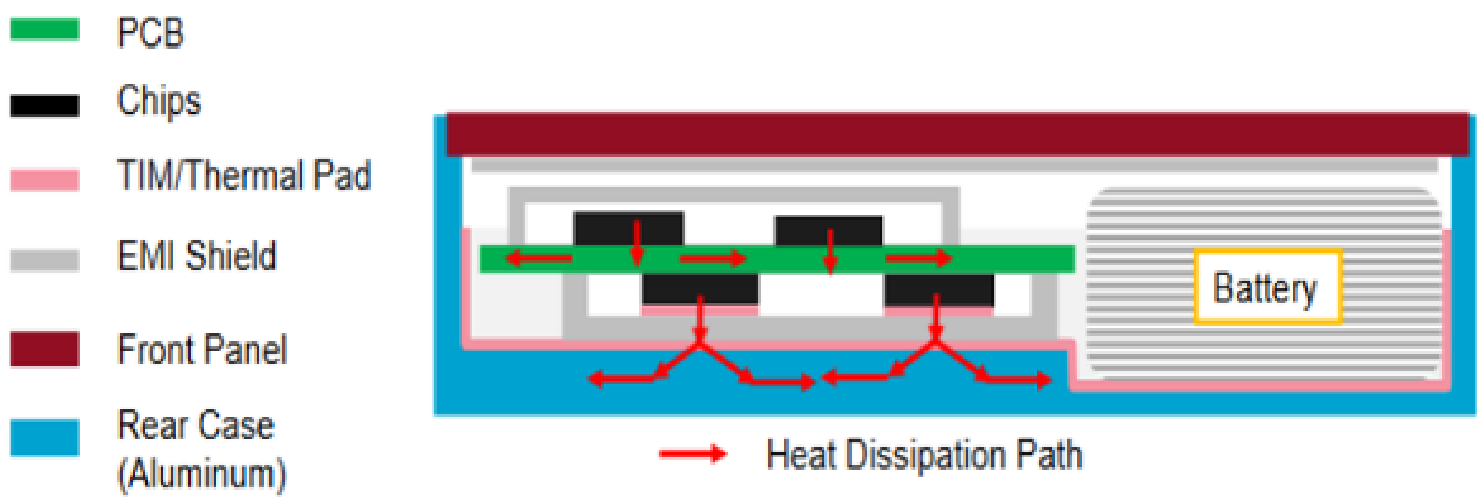


Hitachi Chemicals

Thermal materials for mobile devices

- Conductive path for heat dissipation to aluminum back cover

Chips → TIM Pad → EMI Shield → TIM Liner → Back Cover



Typically: Cu foil for the display and battery, covered by a TIM

Extensive use of graphite sheets

Increased heat dissipation for 5G devices vs 4G

- Heat spreader for the motherboard
- TIM on motherboard for the modem and CPU
- TIM for antenna

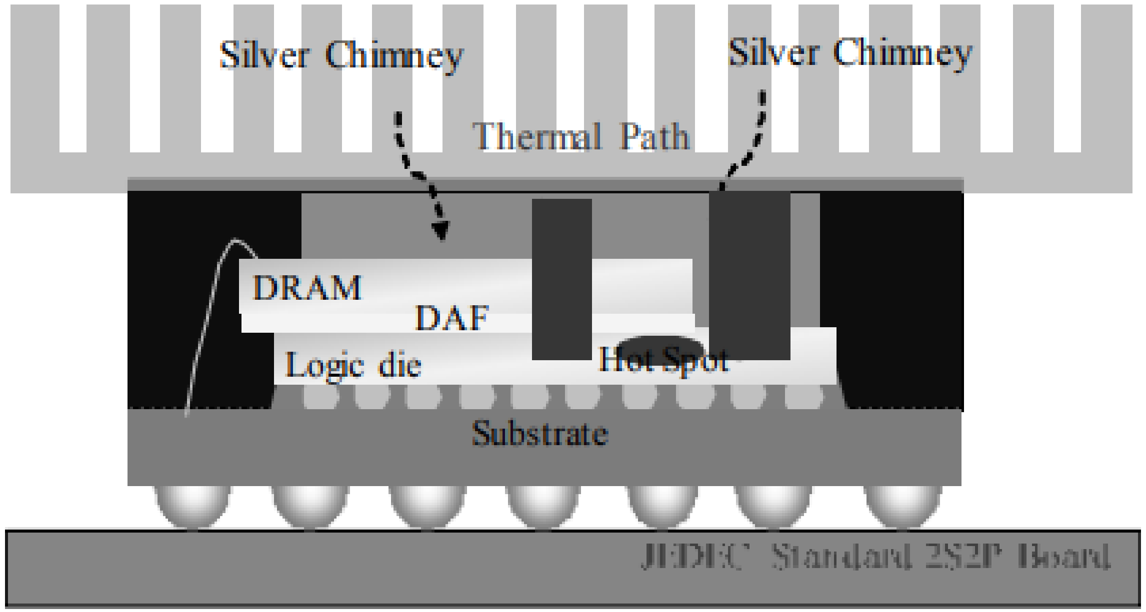
→ Both in- and out-of plane heat dissipation
Controlled surface temperature

Thermal pathways

3D package integration → Increasing prominence with respect to 2D

Thermal pathways on the bottom inherited from 2D intergration

→The top side is the bottleneck (EMC layers)



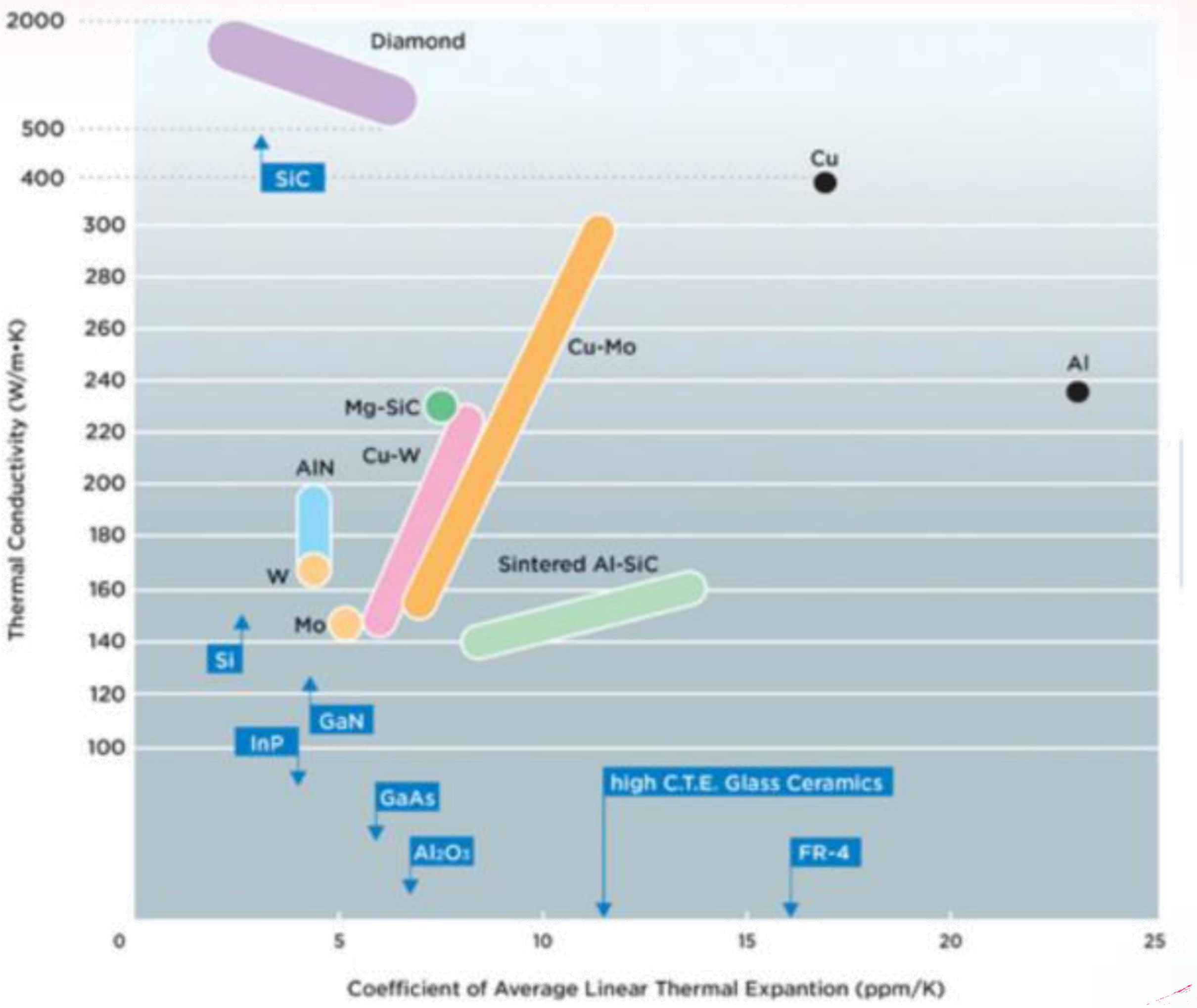
Possible solutions:

- Ag paste based thermal chimneys
- Conductive inks/pastes and ceramic powders

Material development to be done

Choosing a packaging material

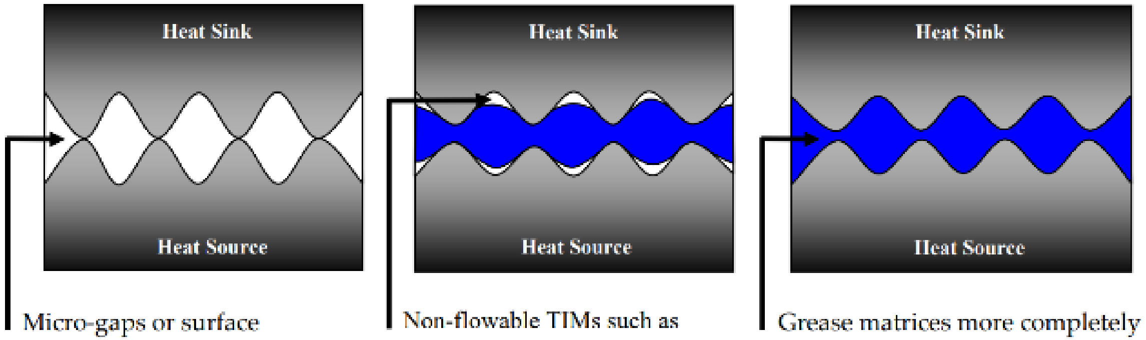
- minimal mismatch required with the heatsink or the slug on which the dies are mounted.
- high mismatch in CTE will cause stress build up during thermal cycles.
- Cu composites (CuW and CuMo) can outperform AlN in terms thermal Conductivity but have a larger CTE
- CTE is well matched with GaAs and reasonable for GaN.



Christian Galvez, Newegg

Thermal interface materials

Considerations for TIMs



Micro-gaps or surface roughness prevent effective heat transfer potentially leading to device failure.

Non-flowable TIMs such as thermal pads may leave voids that inhibit heat transfer

Grease matrices more completely fill micro-gaps to ensure heat flow away from vital parts.

Greases enable thinner bond lines, further reducing thermal resistance.

Types

1. Pressure-sensitive adhesive tapes
2. Thermal adhesives
3. Thermal greases
4. Thermal gels, pastes and liquids
5. Elastomeric pads
6. Phase change materials
7. Graphite
8. Solders and phase change metals
9. Compressible interface materials
10. Liquid metals

Points of consideration

- Bulk Thermal Conductivity
- Low contact resistance.
- Low Bond Line Thickness.
- Application Precision.
- Ease of Manufacture.
- Longevity.
- Reworkability.
- Stress Relief - differential thermal expansion of heat source and heat sink.
- Low Cost.
- Electrical conductivity or dielectric breakdown.

Thermal interface materials

Electrically conductive adhesives (lead-free adhesives)

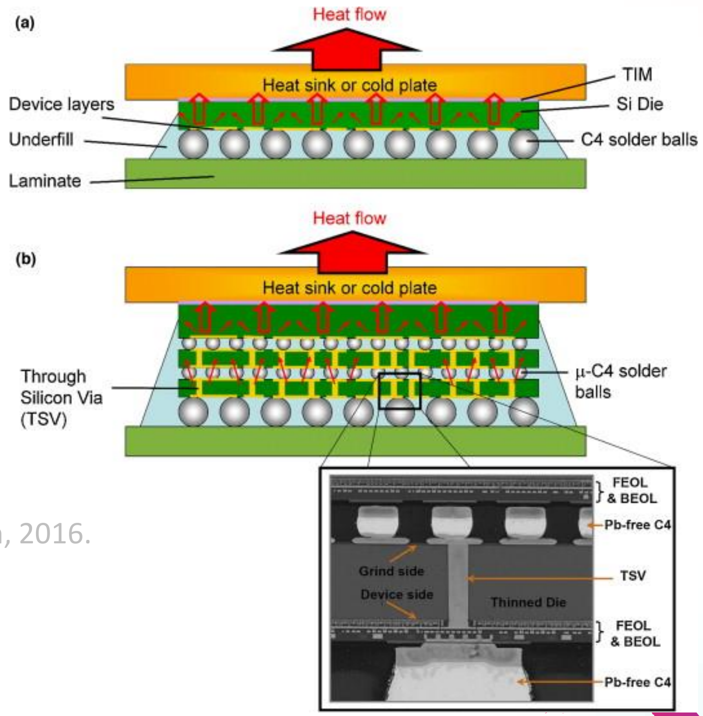
main alternative to solders for advanced electronic packaging technologies, such as chip-on-glass, chip-on-flex and flip-chip attachments [Jain].

Organic matrix (adhesion and structural integrity) and dispersed filler particles (electrical and thermal conductivity).

Typically: thermoplastic or epoxy resin

metallic or carbon-based
(e.g. graphite, carbon fibers, diamond, carbon black or carbon nanotubes)

- A. L. Moore and L. Shi, doi: 10.1016/j.mattod.2014.04.003.
- Z. D. Han and A. Fina, doi: 10.1016/j.progpolymsci.2010.11.004.



Advantages:

- Lower processing temperatures. Usually 120-150 °C, some at room temperature or by radiation [Cui, Petrie].
- Compatibility to substrates such as glasses or ceramics, and other materials which are not wettable by soldering
- Flux-less application. Solders require additional steps. Additionally, fluxes sometimes need removal by cleaning with chlorofluorocarbons (CFC), which are harmful to the environment [Mir].
- No solder

- H.-W. Cui, J.-T. Jiu, S. Nagao, T. Sugahara, K. Suganuma, H. Uchida, and K.A. Schroder, doi:10.1039/C4RA00292J.
- E. M. Petrie, Epoxy Adhesive Formulations. USA: McGraw-Hill Professional, 2005, isbn: 0-07-145544-2.
- I. Mir and D. Kumar, doi: 10.1016/j.ijadhadh.2007.10.004.
- S. Jain, "Isotropically Conductive Adhesive Filled with Silver Metalised Polymer Spheres", Loughborough, University, United Kingdom, 2016.

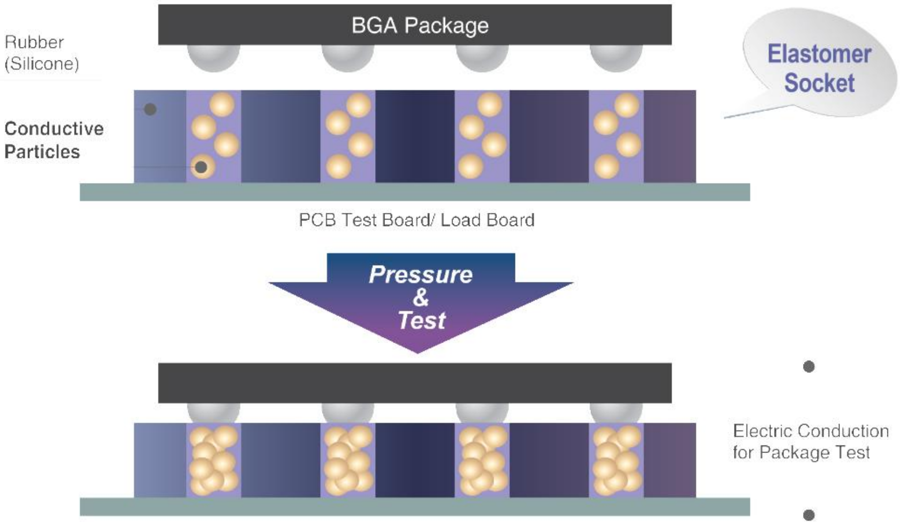
Classification depending on the filler volume fraction:

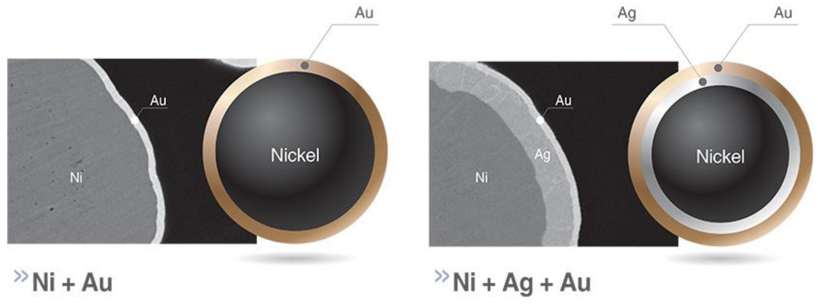
- Low → Non-conductive adhesives
- Medium → Anisotropic conductive adhesives
- High (> percolation thershold) → isotropically conductive adhesive

Thermal interface materials

Elastomer socket powder

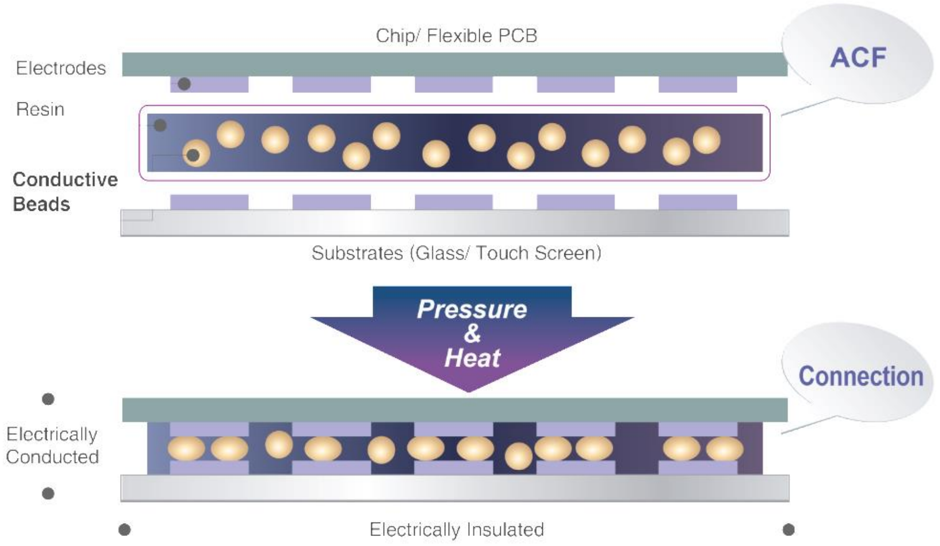
The Elastomer Socket Powder fills the rubber socket for semiconductor testing and plays a role in the electric signal distribution during testing.

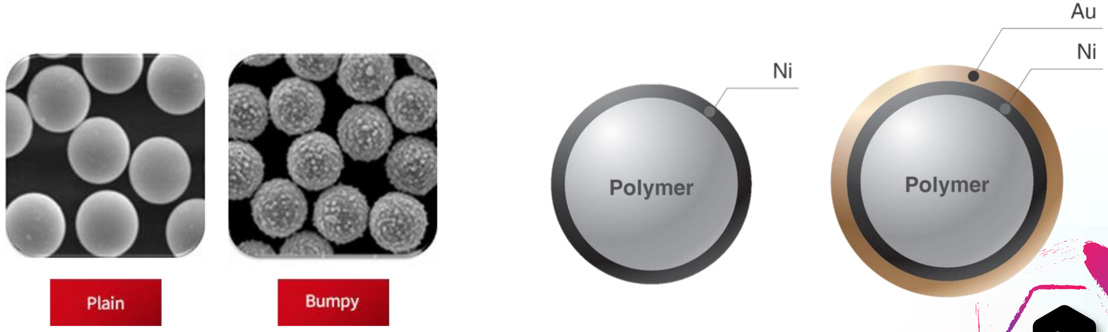




Conductive powder

The conductive bead is a key component of the ACF (Anisotropic Conductive Film) used for electrical and mechanical connections between glass and chip/FPCB on display



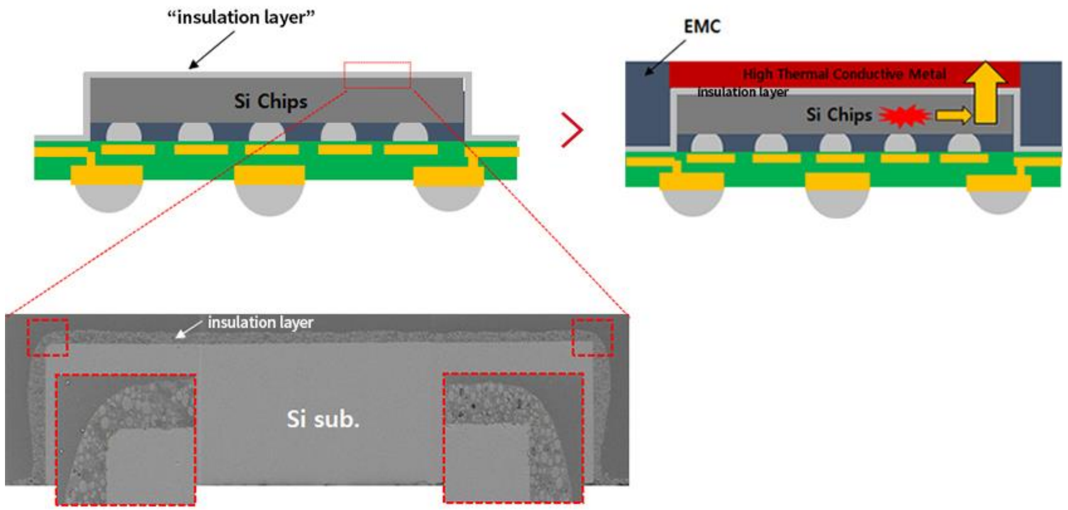


Source: Ntrium

Thermal interface materials

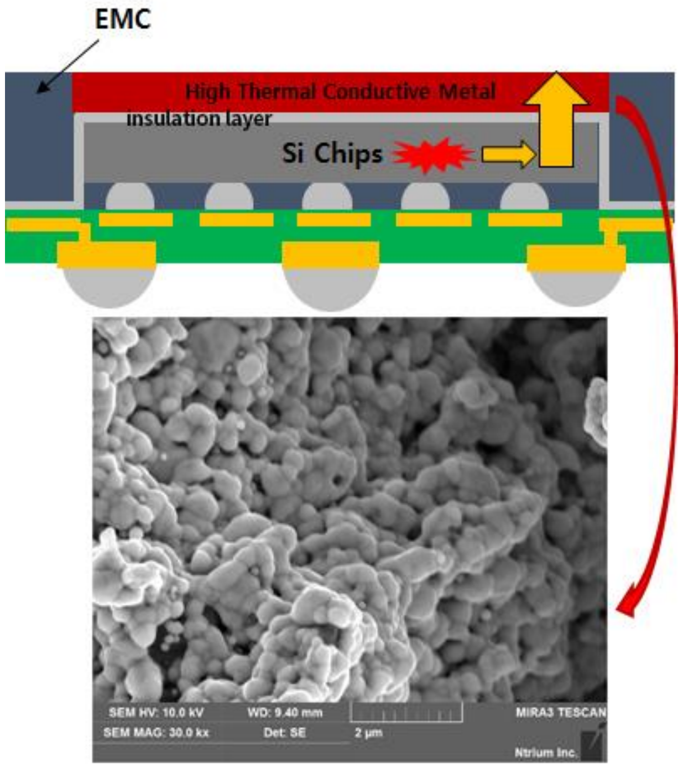
High thermal ceramic paste for spray

Characteristics and Merits
- High Thermal Ceramic Paste (> 3.0W/mK) with high electrical insulation
- Good Spray Applicability - Good Workability / Uniform profile at both surface and edge



High Thermal Ag Sintering Paste

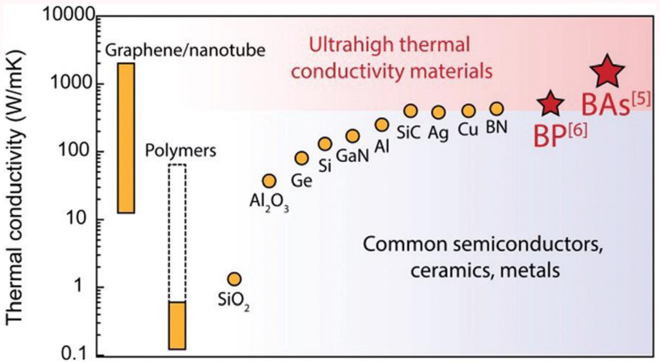
Thermal Coductivity[W/mK]	≥ 50



Source: Ntrium

Ultrahigh thermal conductivity

Heat spreaders for thermal management of high-power electronics:
Primarily synthetic diamond, BN, SiC, Ag, Al, and Cu
Coefficient of thermal expansion should match the heat source

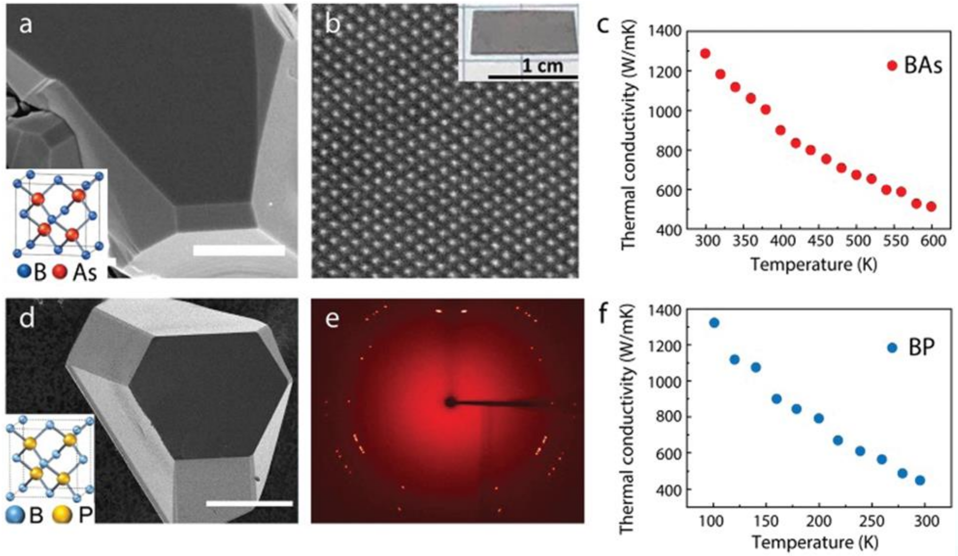


- Synthesis of BAs with a thermal conductivity around 1000 watts per meter-kelvin (originally 200)
- Validation of the search for high-thermal-conductivity materials and enhanced ease of integration into semiconducting devices.

Physics

Origin of high-k:
acoustic phonon bunching combined with large acoustic-optical gaps (Lindsay)

T dependence of κ steeper than T^{-1}
→ κ limited by four-phonon scattering (Feng, Kang)



Directions

- High quality Bas (with high thermal interface conductance)
- BAs powders for metal matrix composites, small particles (e.g., 50 µm diameter).

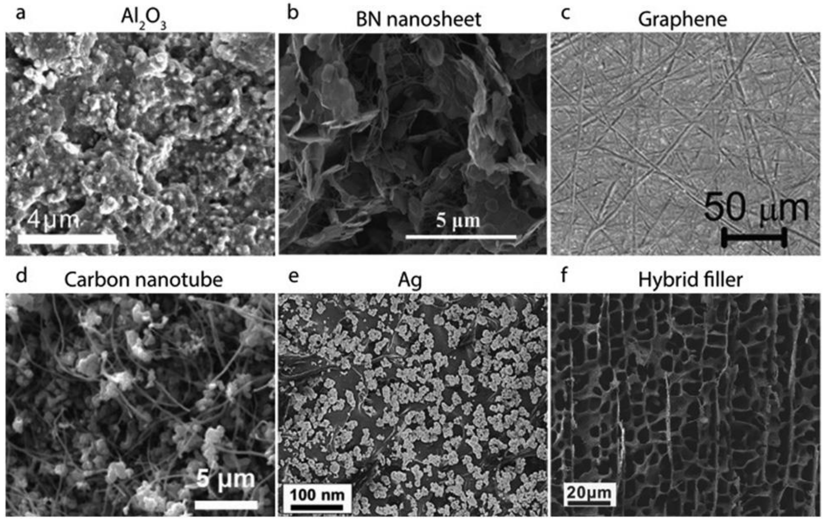
L. Lindsay, D.A. Broido, T. L. Reinecke, *Phys. Rev. Lett.* 111, 025901 (2013).
T. L. Feng, L. Lindsay, X. L. Ruan, Phys. Rev. B 96, 161201 (2017).
J. S. Kang et al., Science 361, 575 (2018).

2D Materials

2D Materials for thermal management

Fillers for Polymer-Based TIMs

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

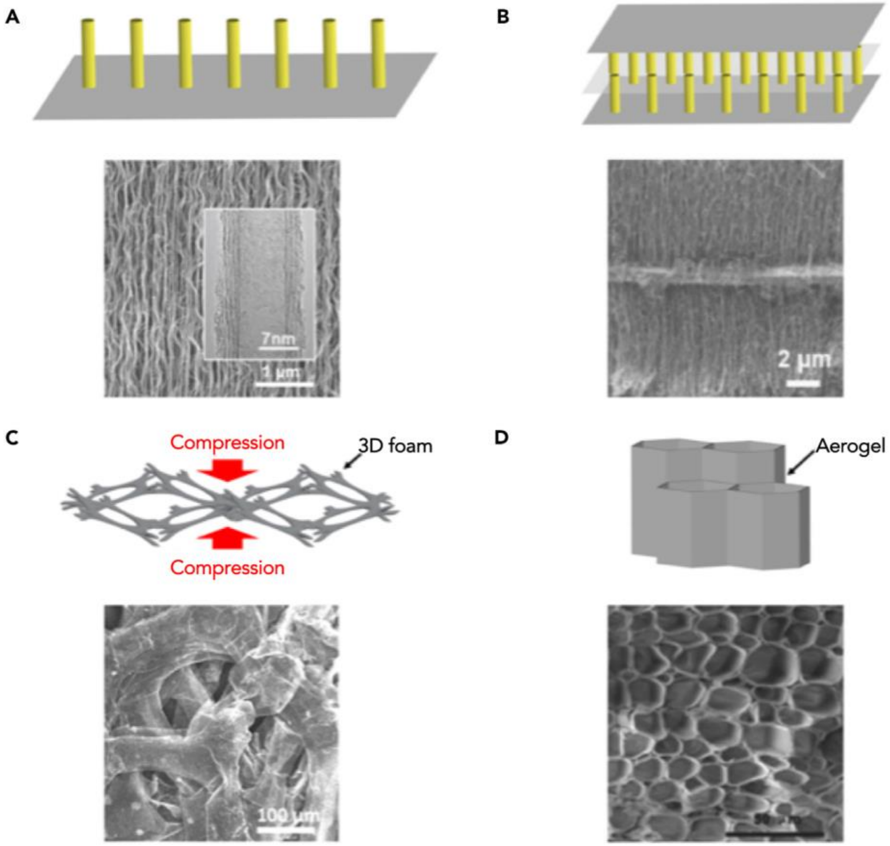


high κ with minimized filler loading

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

Direct Use for Thermal Management

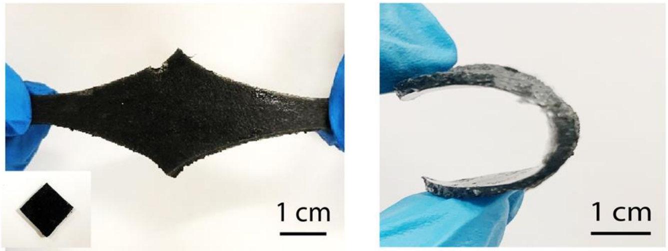
2D Materials and 3D assemblies

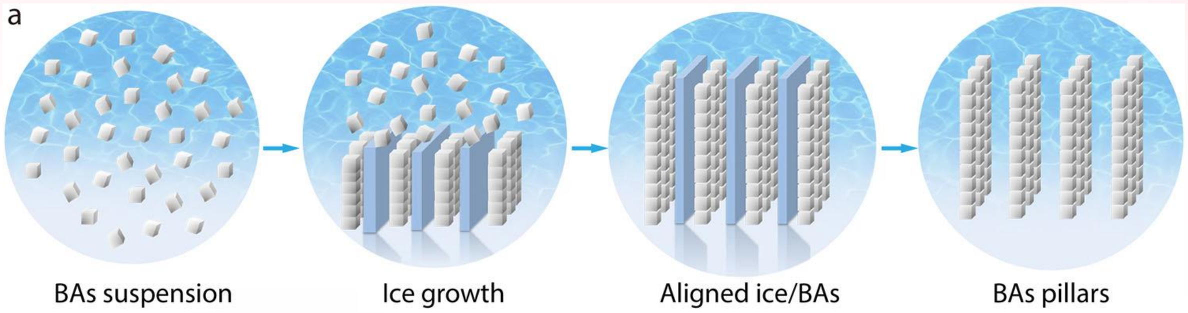


- 3D-Interconnected Graphene and H-BN Macroforms
  Graphene and h-BN Thin Films for Heat Spreaders
- Graphene Fibers for Thermal Management

Developments in thermal management

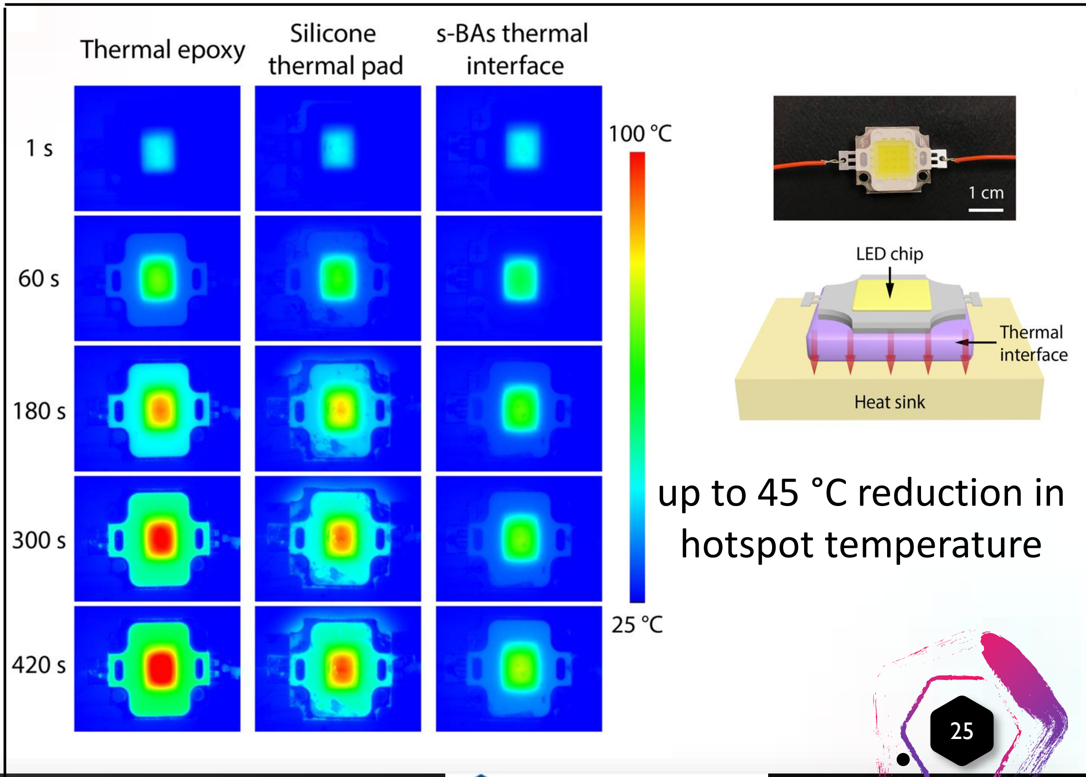
Flexible thermal interface based on self-assembled boron arsenide





Self-assembled cubic boron arsenide (s-BAs) microcrystals in polymer composite:

- thermal conductivity up to 21 W/m·K
- elastic compliance down to 100 kPa
- high flexibility for flexible devices
- scalable manufacturing



up to 45 °C reduction in hotspot temperature

Nat. Commun. **12**, 1284 (2021)

Comparison of thermal interface materials

Property	Tapes	Liquid Adhesives	Greases	Gels and Pastes	Elastomeric Pads	Phase Change Materials	Graphite	Solders	Compressible Metals	Liquid Metals
Bulk Thermal Conductivity	Fair	Fair	Excellent	Good	Excellent	Good	Excellent	Excellent	Excellent	Excellent
Low Interfacial Resistance	Poor	Excellent	Good	Good	Fair	Excellent	Fair	Excellent	Excellent	Excellent
Low Bond Line Thickness	Fair	Good	Poor	Good	Poor	Excellent	Excellent	Good	Excellent	Poor
Application Precision	Excellent	Poor	Poor	Poor	Excellent	Excellent	Good	Poor	Good	Poor
Ease of Manufacture	Good	Fair	Poor	Fair	Good	Good	Good	Fair	Good	Good
Longevity	Fair	Fair	Poor	Fair	Fair	Fair	Excellent	Good	Good	Fair
Reworkability	Poor	Good	Good	Good	Excellent	Excellent	Poor	Fair	Fair	Fair
Stress Relief	Fair	Fair	Poor	Excellent	Good	Good	Fair	Good	Good	Good
Low Cost	Good	Good	Excellent	Good	Good	Fair	Fair	Fair	Fair	Poor

Summary

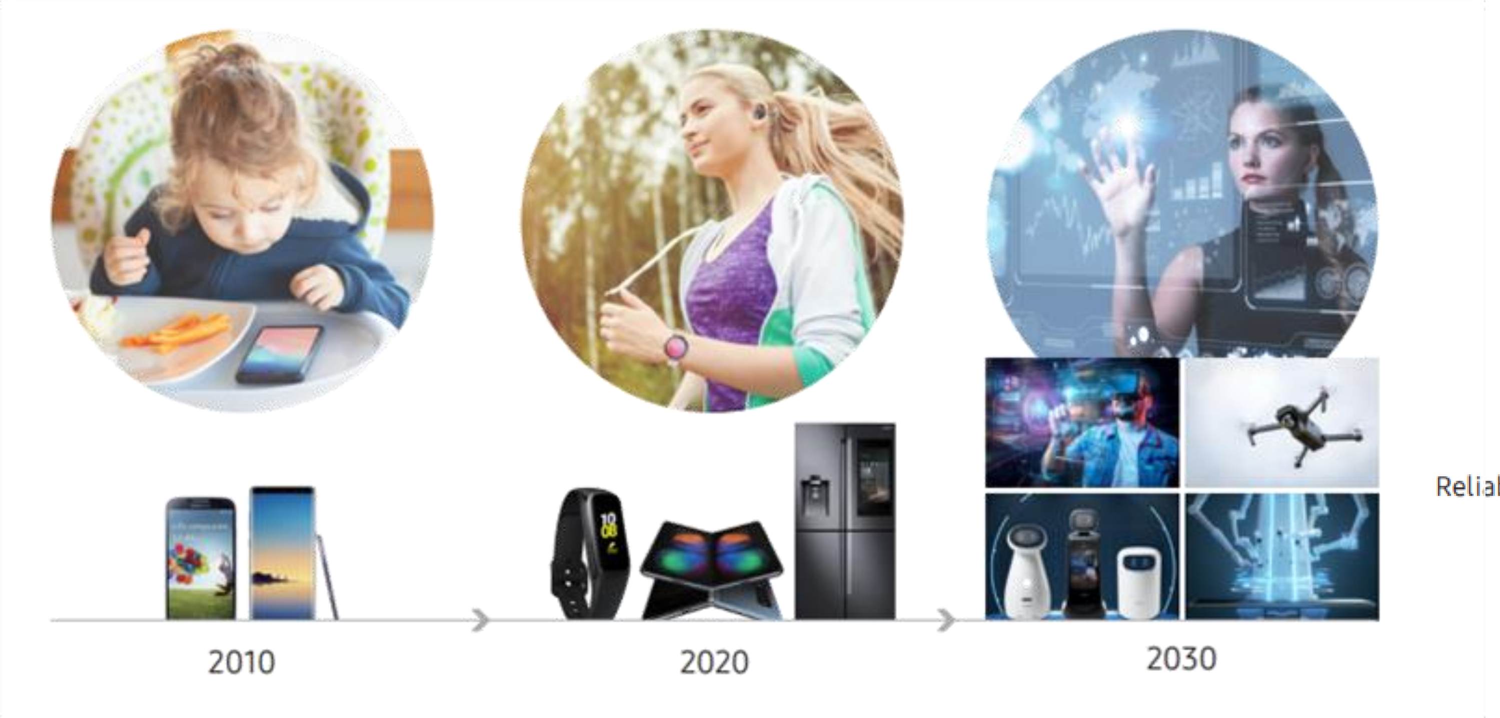
Thermal management strategy on different levels

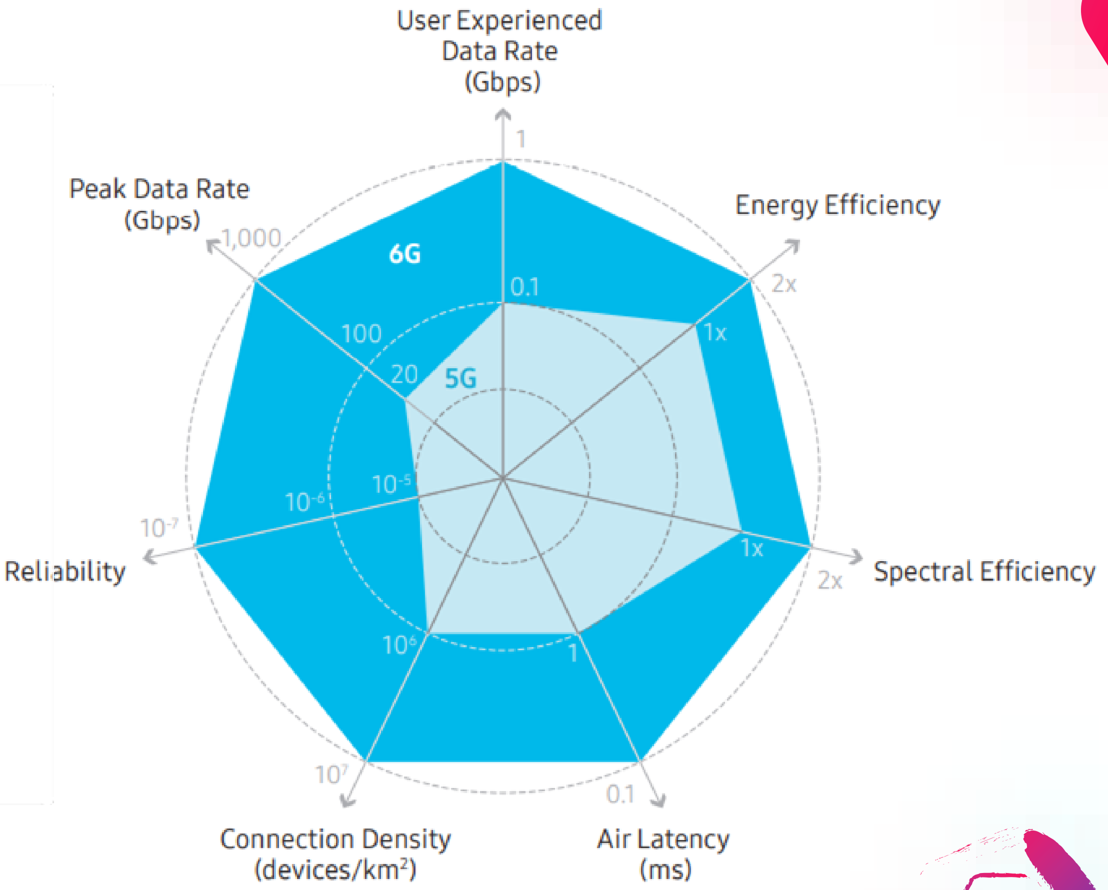
- Device level
- Chip or package level
- Material design

Passive cooling is complemented by active solutions

6G: the future of mobile devices is THz?

Towards THz communications in the 2030s





Source: 6G Samsung, nextimpact.com

Merci

Jérémie Maire

Jeremie.maire@u-bordeaux.fr

GDR NAnoMaterials for Energy applications

5G rollout: Thermal materials and solutions

- **In-Package Heat Dissipation**
- **Thermal Interface Materials**
- **Thermal Management for Mobile Devices**