# "Electro-thermal Applications of Nanomaterials"

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## Electro-thermal applications

- Integrated Circuits
- Sensors
- Actuators

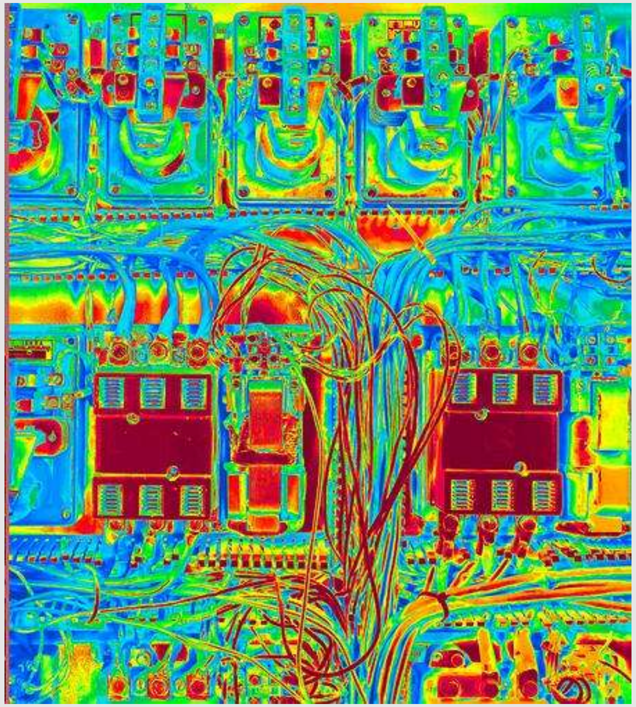
Electro-thermal modelling

Carbon-based materials for electro-thermal applications

Simulation and characterization evidence

## Electro-thermal effects and applications: heat management in printed circuit boards

**Issue**: high temperatures and hot spots




**Solutions**:

**Passive heat removal:**

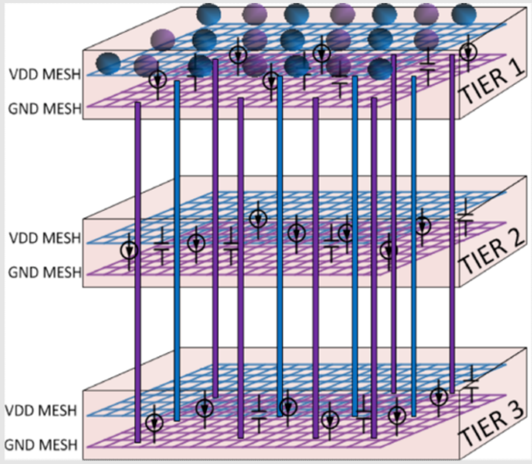
- Materials (new materials)
- Architectures (layouts, heatsink, thermal interfaces,…)

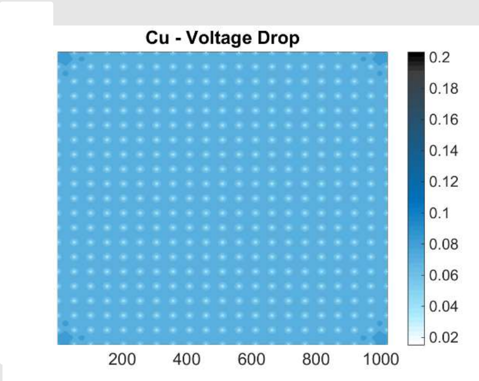
**Active heat removal**

- cooling systems

# Electro-thermal effects and applications: heat management in integrated circuits

**Issue**: power & signal integrity



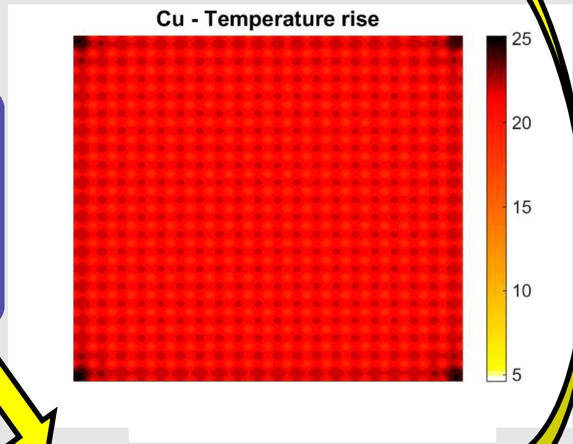




**Heat production for Joule effect**

$$F = \rho(T) J^2$$

**Temperature rise**

$$\nabla \cdot (k \nabla T) + c \frac{\partial T}{\partial t} = F$$




**Resistivity increases with T**

$$\rho(T) = \rho_0 [1 + \alpha_0 (T - T_0)]$$

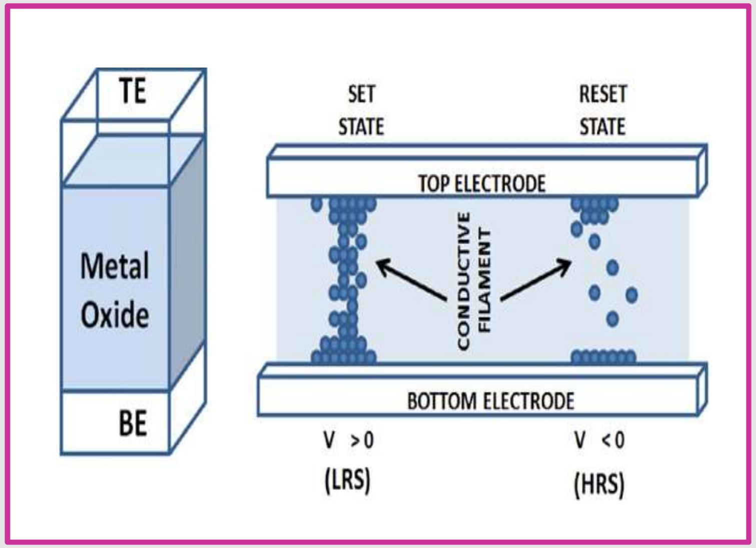
**Error in reference voltage**

$$V_d = V_{ideal} - V_{real}$$

# Electro-thermal effects and applications: temperature-based devices

## Resistive Random Access Memory

The **resistance value** is associated to a conductive filament made by **ions** emitted by the **active electrodes** under the action of the applied voltage

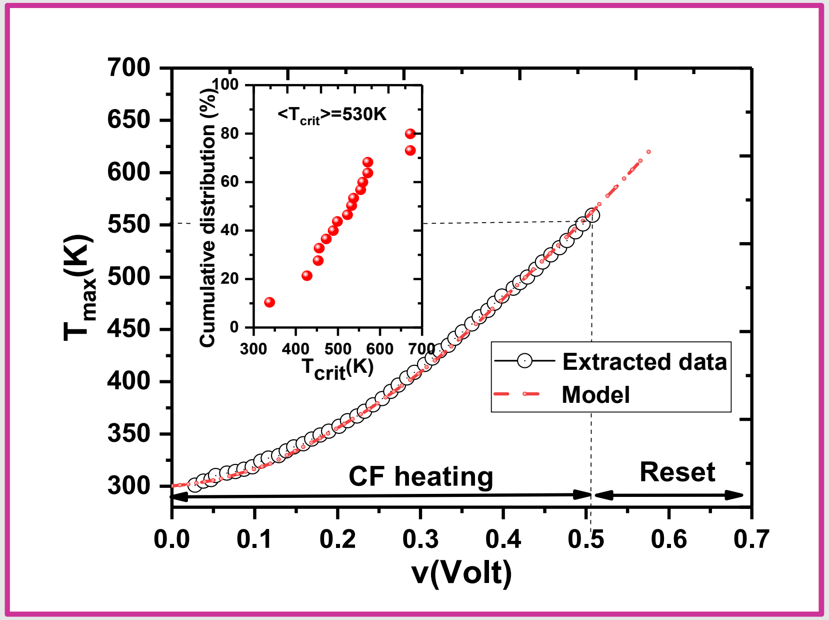



**SET:** Switching to Low Resistance State (LRS)

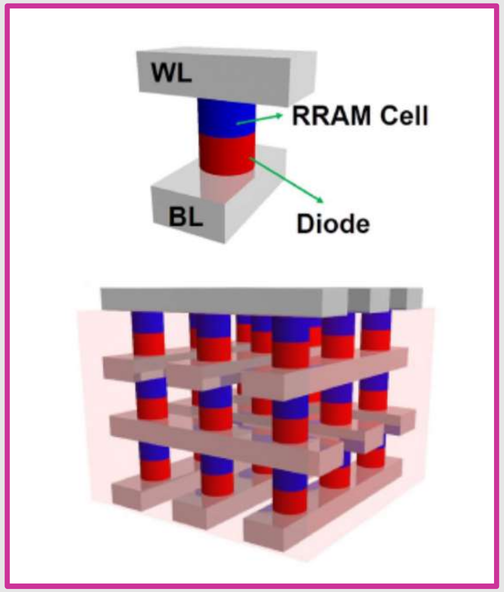
**RESET:** Switching to High Resistance State (HRS)

The **reset** occurs when a critical temperature is reached:

**NEED for a strict control of the temperature distribution**



# Electro-thermal effects and applications: Resistive Random Access Memory

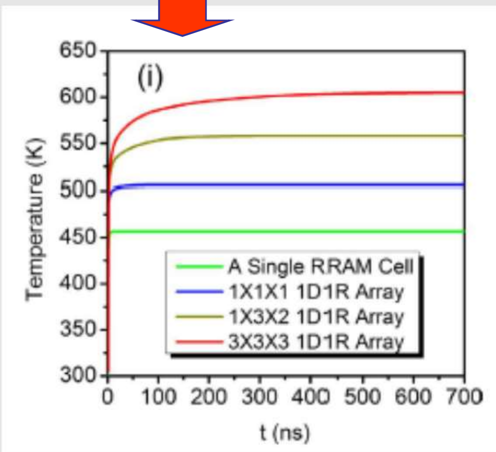



**PRO**

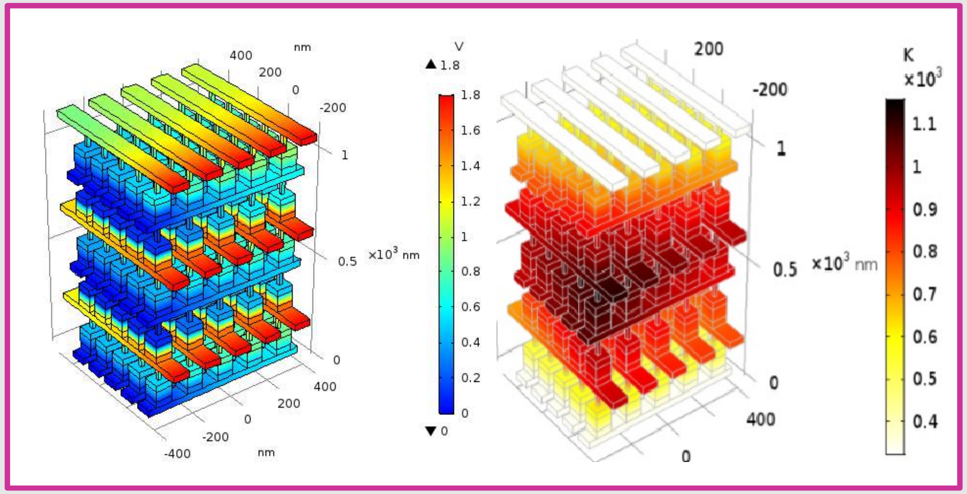
- Good selectivity
- Robustness vs sneaky currents

**CONS**

- Only for unipolar switching
- Voltage drop over the diode
- Thermal issues:
  - **- temperature increase**




*P. Sun et al.,*
**Scientific Reports, 2015**

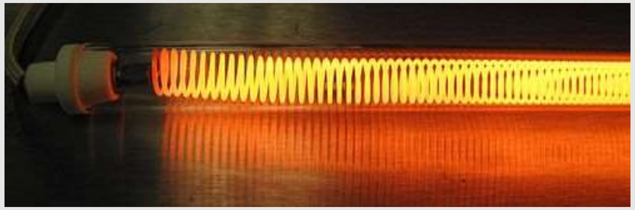


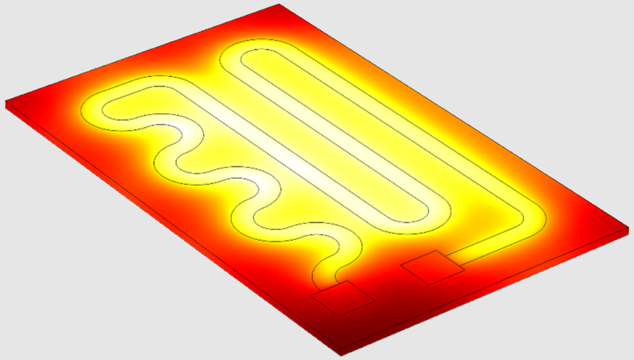

**thermal crosstalk**

***F. Zayer, K.Lahbacha, W. Dghais, H. Belgacem, M. de Magistris, A. Melnikov, A. Maffucci,*** **IEEE Trans. Electron Devices, 2021**

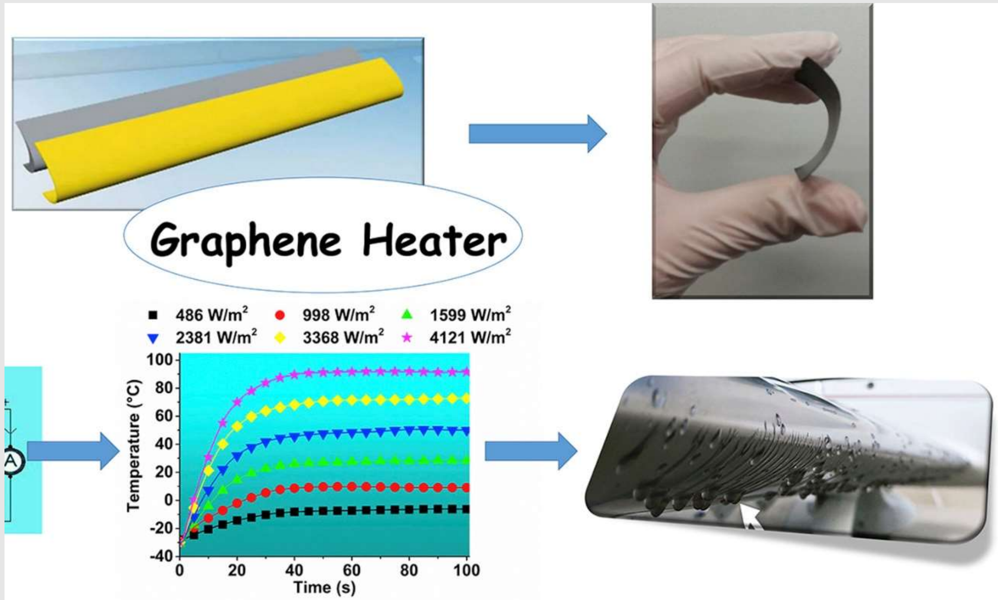
# Electro-thermal effects and applications: actuators

heating elements based on Joule effect





De-icing heaters for airplane wings




*L. Vertuccio et al.,*
**Composites B, 2019**

# Electro-thermal effects and applications: sensors

## Thermristors

A type of resistor with resistance varying with temperature.

**Temperature sensing** is achieved by measuring the change in resistance:

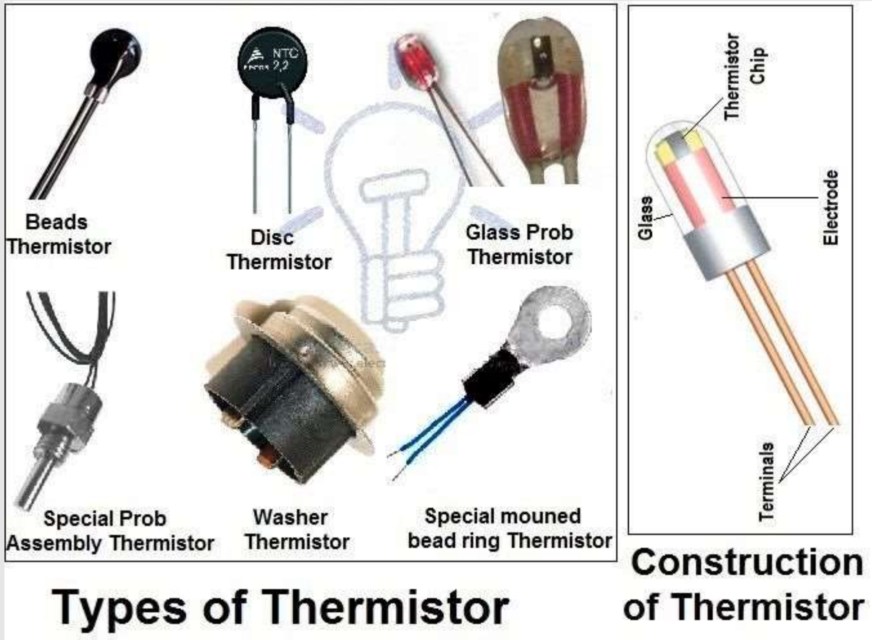
$$\Delta R = k\Delta T$$

where

$\Delta R$ = change in resistance

$\Delta T$ = change in temperature

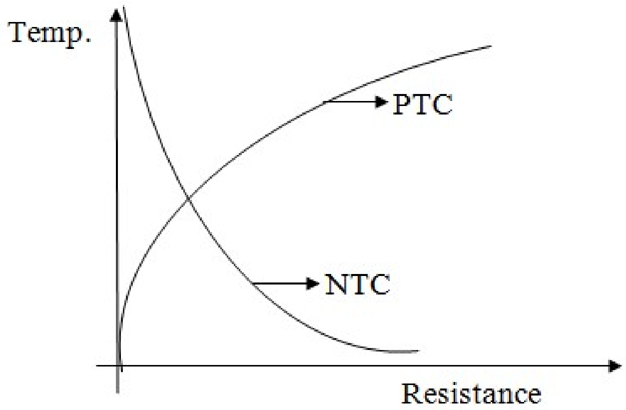
$k$ = first-order temperature coefficient of resistance



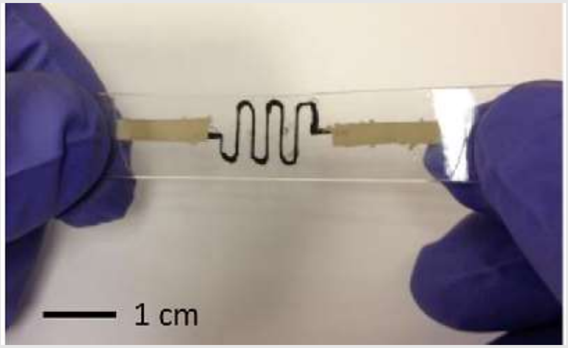
## Thermristor types: NTC and PTC

A **NTC thermistor** is one in which the zero-power resistance decreases with an increase in temperature → **Mostly used in temperature sensing**

A **PTC thermistor** is one in which the zero-power resistance increases with an increase in temperature → **Mostly used in electric current control**




**NTC Thermristors**

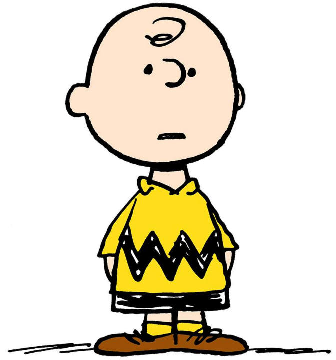



*C. Yan et al.*, **ACS NANO, 2015**

Electro-thermal applications

**Electrothermal modelling**

- **Multiphysics modelling**
- **Relaxation technique**
- **Equivalent circuit modelling**
- **Reduced order modelling**



Simulation and characterization evidence

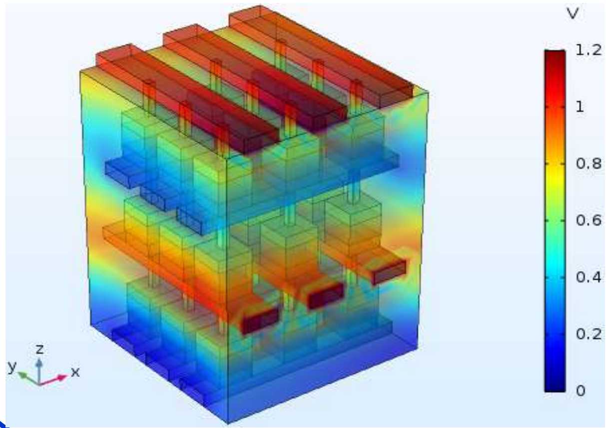
Carbon-based materials for electro-thermal applications

# A «multiphysics» problem

**Electrical model**

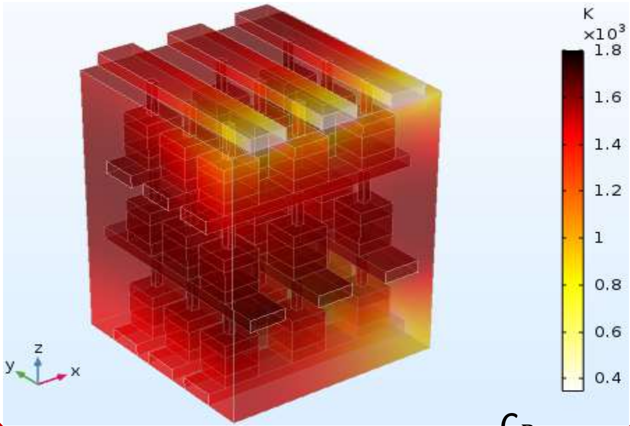
$$\nabla \cdot \boldsymbol{J} = -dQ/dt \quad \boldsymbol{E} = \rho(T)\boldsymbol{J}$$

$$\boldsymbol{E} = -\nabla V \quad \rho(T) = \rho_0[1 + \beta(T - T_0)]$$




**Thermal model**

$$\rho c_P\, \partial T/\partial t - \nabla \cdot \kappa \nabla T = Q_S$$




$c_P$

$$Q_S = \boldsymbol{J} \cdot \boldsymbol{E} = \rho J^2$$

**coupling term**

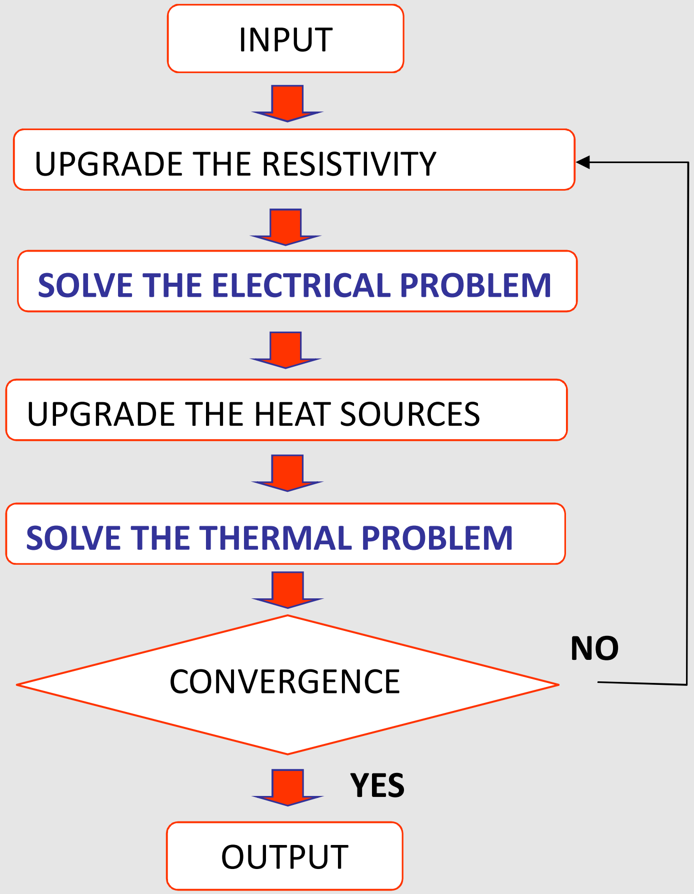
# An iterative approach (relaxation technique)

**Main coupling mechanism**

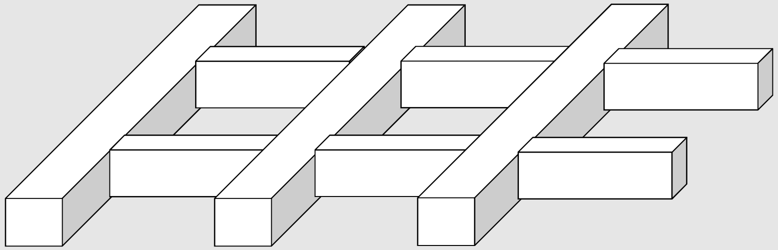
**Temperature Variation**

↓

**variation of the electrical resistivity**



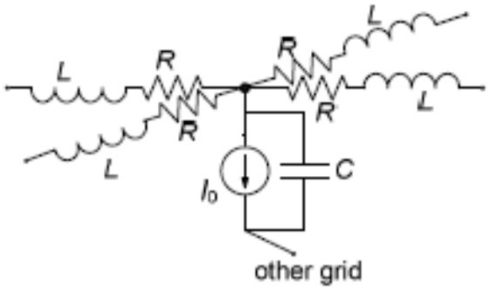
# An equivalent circuit model: the example of a Power Delivery Network



**for each PDN track:**

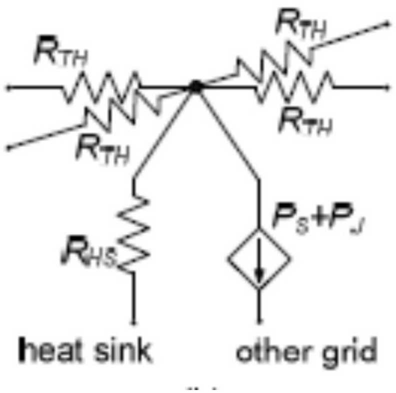
- A thermal resistance (thermal conductivity $K_m$)
- Power grid branch < characteristic thermal length, $L_H$
- **Heat sources** modeled as current sources
- Package represented by a thermal resistance.

**Electrical circuit model**




**Electrical network node**

**Thermal circuit model**




**Thermal network node**

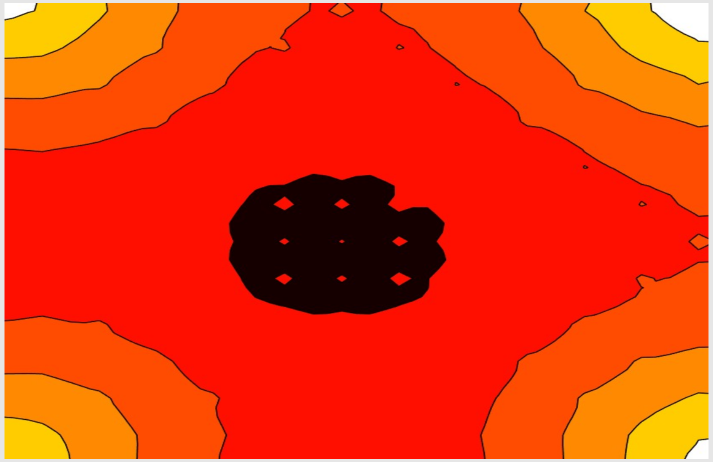
A (discretized) thermal problem is equivalent to an electrical network, where

V ↔ T and I ↔ p

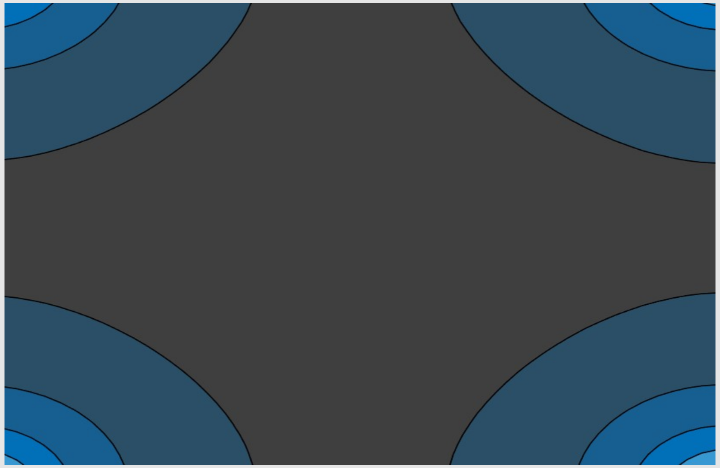
# Model-order reduction via clustering

**Step 1: Steady state solution for the full PDN**

**Temperature map**



**Voltage drop map**



For a given frequency, the **ET steady-state problem** reduces to a system of linear algebraic equations, with sparse matrices

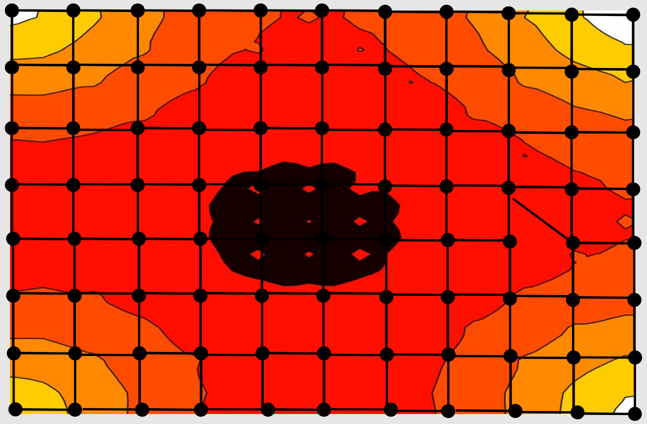
**→ the ET problem is efficiently solved by numerical solvers with a limited cost**

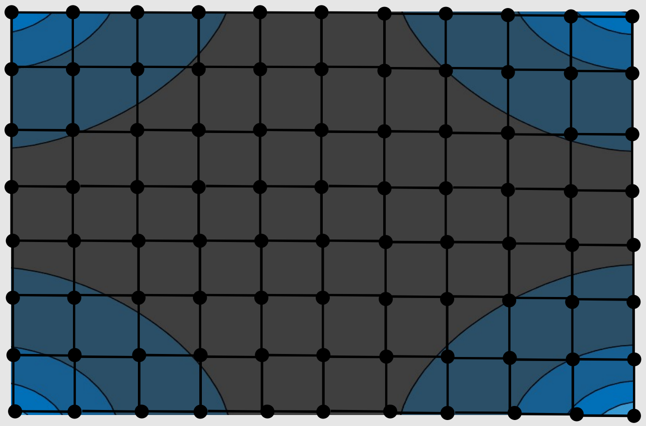
# Model-order reduction via clustering

**Step 2: Define a quantization level**

$$\Delta T_r = \left(T_{r,\max} - T_{r,\min}\right)/(N_T - 1).$$

$$\Delta V_d = \left(V_{d,\max} - V_{d,\min}\right)/(N_V - 1)$$





$N_T$ quantization levels for temperature

$N_V$ quantization levels for voltage drop

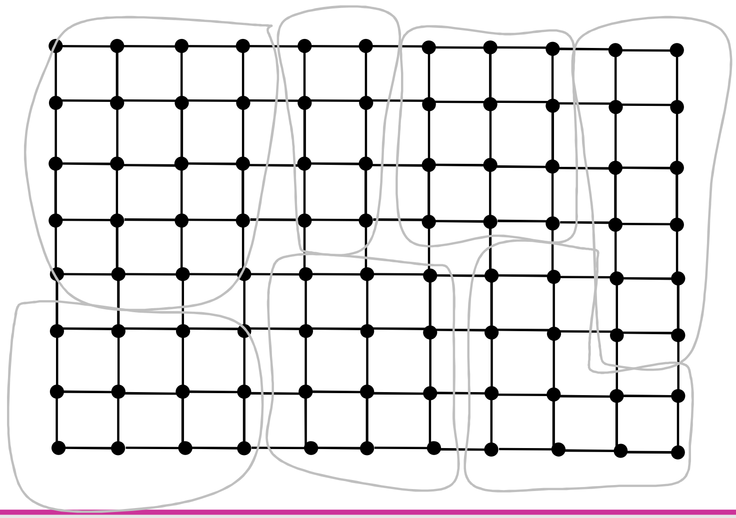
# Model-order reduction via clustering

**STEP 3: cluster the network nodes into supernodes**

**Thermal network**

**Cluster** into supernode *h* each node *j* such as

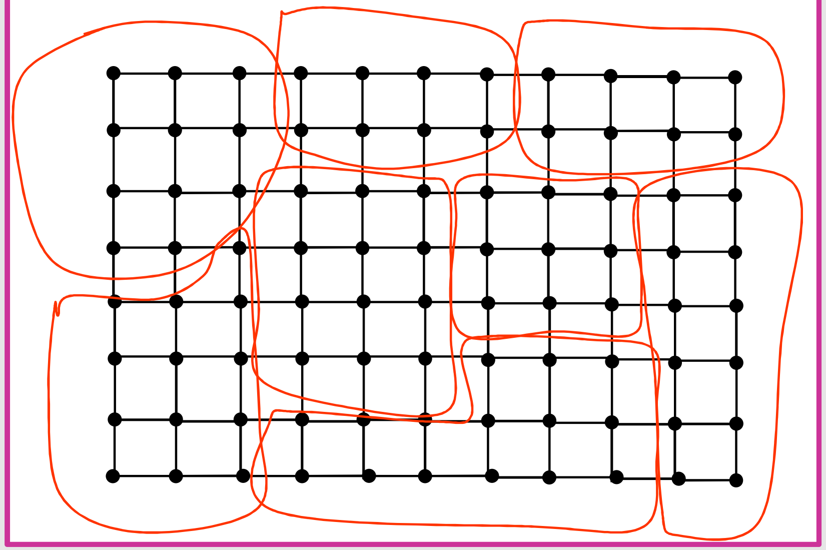
$$\left|T_r(j) - T_{rh}\right| \le \Delta T_r$$



**Electrical network**

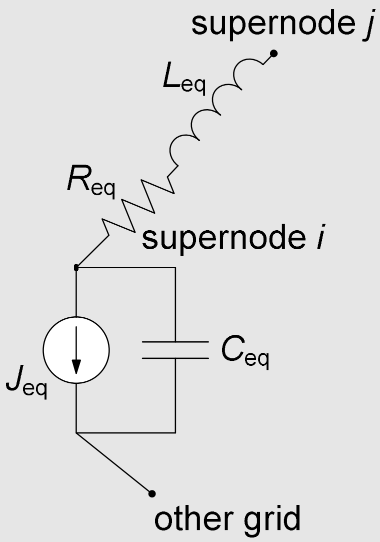
**Cluster** into supernode *k* each node *i* such as

$$\left|V_d(i) - V_{dk}\right| \le \Delta V_d$$



# Model-order reduction via clustering

**STEP 4: build the matrices of the reduced circuits**




**Incidence matrix**

$$\mathbf{A}_e(m,n) = \begin{cases} \pm 1 & \text{supernodes } m,n \text{ are connected} \\ 0 & \text{supernodes } m,n \text{ are not connected} \end{cases}$$

**Admittance matrix**

$$Y_e(m,n) = \begin{cases} \sum_{i,j}^{N_V} Y_e(i,j) & \text{node } i \text{ belongs to supernode } m, \text{ node } j \text{ belongs to supernode } n \\ 0 & \text{supernodes } m,n \text{ are not connected} \end{cases}$$

**Current source vector**

$$I_{0e}(n) = \sum_{i}^{N_V} I_{de}(i) \quad \text{node } i \text{ belongs to supernode } n$$

**The same approach is applied for the thermal network**

# Model-order reduction via clustering

**Step 5: synthesize and solve the final SPICE model**

**Reduced electrical network MNA model**

$$\mathbf{Y}_{er} = \mathbf{A}_e^T \mathbf{Y}_e \mathbf{A}_e$$

$$\mathbf{Y}_{er} \underline{V}_d = \underline{I}_0$$

The model is synthesized in SPICE to perform power integrity analysis and noise analysis

Summarizing…

**STEADY-STATE COMPLETE ELECTRO-THERMAL NETWORK**

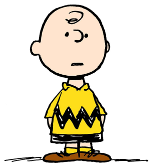
**REDUCED STATIC THERMAL NETWORK**

**REDUCED DYNAMIC ELECTRICAL NETWORK**

**SPICE MODEL**

*A. Maffucci, A. Magnani, M. de Magistris, A. Todri-Sanial,* **IEEE T-NANO, 2016**

Electro-thermal applications



Electrothermal modelling

**Carbon-based materials for electro-thermal applications**

- **Graphene and carbon nanotubes**
- **Graphene nanoplatelets**
- **Modelling the electro-thermal behavior**

Simulation and characterization evidence

## Superior thermal and electrical properties of nanomaterials

| | Si | Cu | Carbon Nanotubes | Graphene |
|---|---|---|---|---|
| **Max current density ($A/cm^2$)** | -- | $10^7$ | $10^9$ | $10^8$ |
| **Mean free path @ T=300 K (nm)** | 30 | 40 | $10^3$ - $2.5 \cdot 10^4$ | $10^3$ |
| **Melting point (K)** | 1687 | 1356 | 3800 | 3800 |
| **Thermal conductivity (kW/mK)** | 0.15 | 0.38 | 1.7 - 5.8 | 3.0-5.0 |

For their outstanding electrical and thermal properties, graphene and carbon nanotubes are proposed for:

**Thermal interface materials (packaging)**

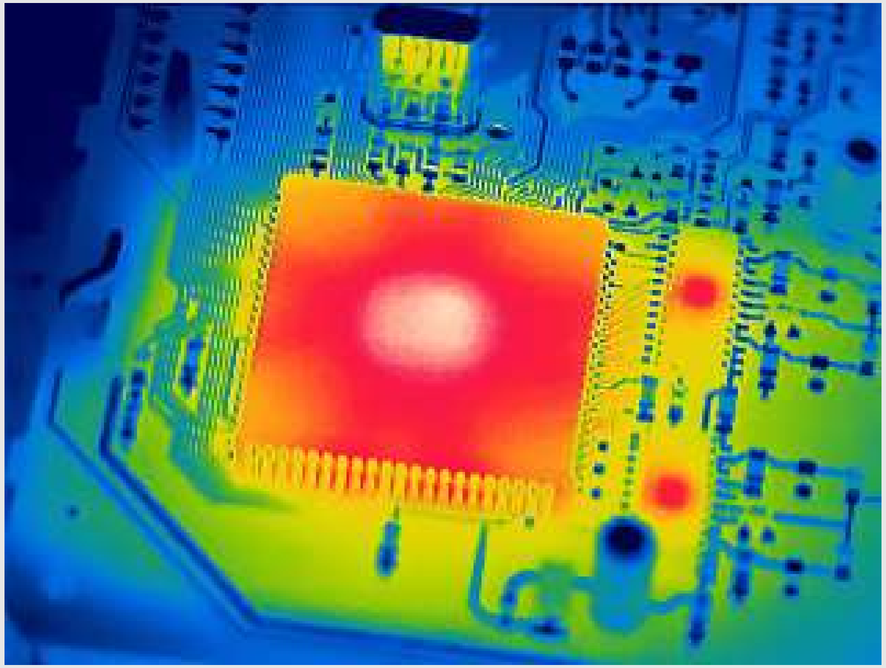
**NTC Thermristors (sensors)**

**Heaters (de-icing)**

## Thermal management in electronics

### Example: thermal management in packages

In ultrascaled VLSI technology the **current densities** are of the order of **MA/cm²**, leading to a volumetric **heat production** of the order of **$10^3$-$10^4$ W/mm** (ITRS)



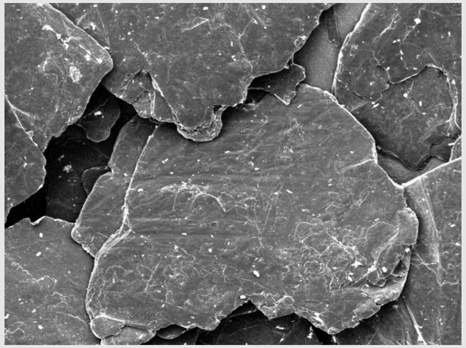
**MAIN BENEFITS FROM USING CARBON:**

- **Carbon interconnects**: may carry a density of current 2 order of magnitude higher that Cu ones, while reducing the heat production (due to stability of resistance with temperature)
- **Graphene TIM:** thermal interface materials based on GNP may increase efficiency of heat transfer by 80 percent

# Industrial graphene: technological limits

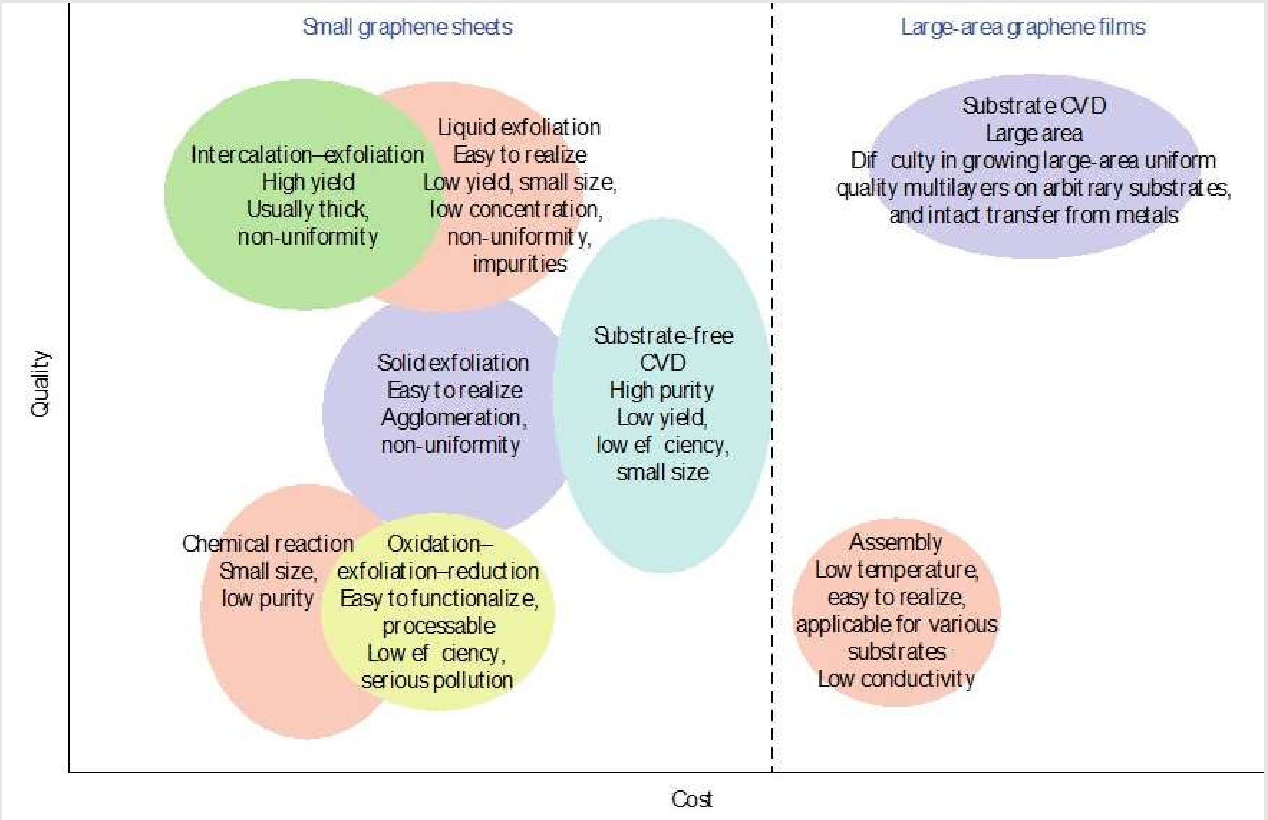
The industrial production of large graphene films is **not realistic** due to the costs

Low-cost graphene-like materials are proposed such as **Graphene Nanoplatelets (GNPs)**



**Typical sizes**
- **plane: 5 - 10 μm**
- **Thickness: 20-50 nm**

Films of low-cost graphene may be realized starting from GNPs




*W. Ren, H.-M. Cheng,* **Nature Nanotechnology, 2014**

# Modelling the electrical resistivity vs temperature: conventional materials

**OHM's law (from Drude model) for temperature *T* varying**

$$\boldsymbol{E} = \frac{m_e}{e^2 n\tau}\boldsymbol{J} = \rho \boldsymbol{J}$$

$$\rho = \frac{m_e}{e^2 n\tau} = \frac{m_e v_e(T)}{e^2 n l_{mfp}(T)}$$

$v_e(T)$ → Velocity (increases with *T*)

$l_{mfp}(T)$ → mean free path (decreases with *T*)

The resistivity is always an increasing function of temperature (PTC)

## Linear approximation

$$\rho(T) = \rho_0[1 + \beta(T - T_0)]$$

$\rho_0$ = resistivity at $T=T_0$

$\beta$ = temperature coefficient

| $T_0$ = 20 °C | Bulk W>160 nm | W = 44 nm | W = 22 nm |
|---|---|---|---|
| $\rho_0$ $(10^{-8}\ \Omega\mathrm{m})$ | 1.68 | 3.29 | 6.01 |
| $\beta$ $(K^{-1})$ | 0.0039 | 0.0016 | 0.0012 |

**Values for a copper wire of width W**

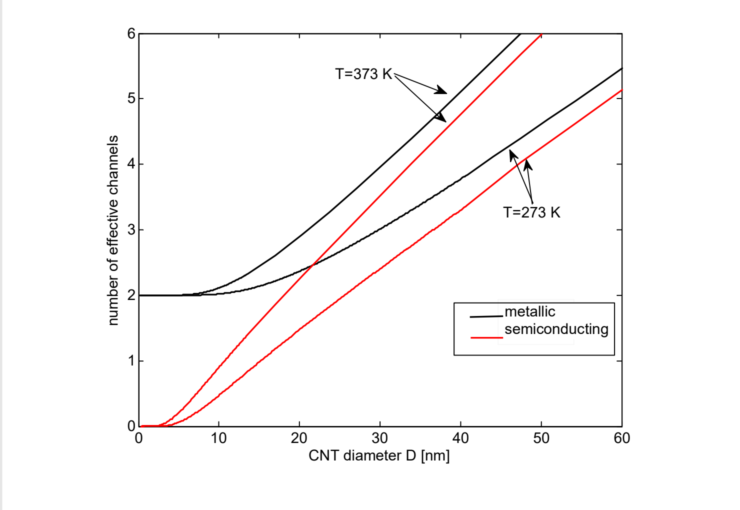
# Modelling the electrical resistivity vs temperature: carbon nanotubes

**Electrical resistance model** for a carbon nano-interconnect

contact → distributed

$$R = R_C + R'_{TL} \cdot len = \frac{R_0 + R_p(T)}{M(T)} + \frac{R_0}{2M(T)l_{mfp}(T)} len$$

$M(T)$ **number of conducting channels:** is independent from $T$ or increases with $T$ → **Example: MWCNT of large diameter D** →




$l_{mfp}(T)$ **mean free path:** decreases with $T$ → **Example: metallic CNT of diameter D** $l_{mfp}(T) = D[k_1 + k_2T + k_3T^2]^{-1}$

$R_p(T)$ **parasitic contact resistance:** increases with $T$ → **Example: side type electrode/CNT contact** $R_p(T) = \frac{r_p}{S_c}\left(1 + \alpha_p (T - T_0)\right)$

The counteracting behavior of these parameters may lead to **any sign for TCR**

# Temperature Coefficient of the Resistance: CNT vs Cu interconnects

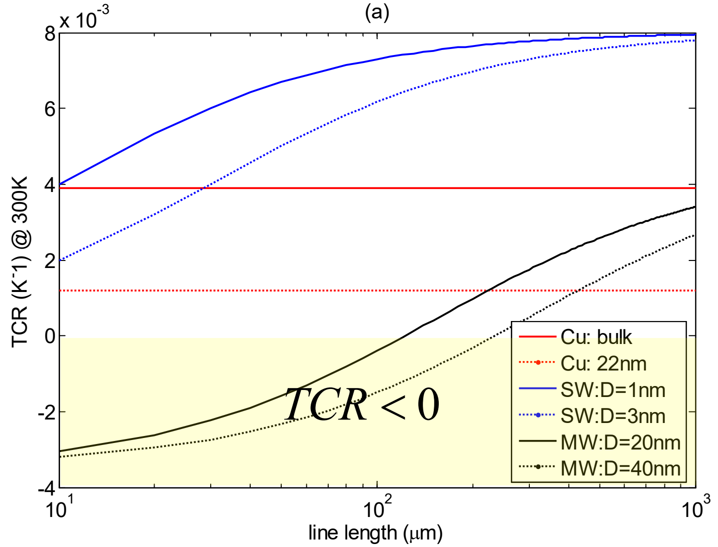
**Temperature Coefficient of the Resistance**

$$TCR(T^*) = \left.\frac{\partial R / R}{\partial T}\right|_{T=T^*}$$

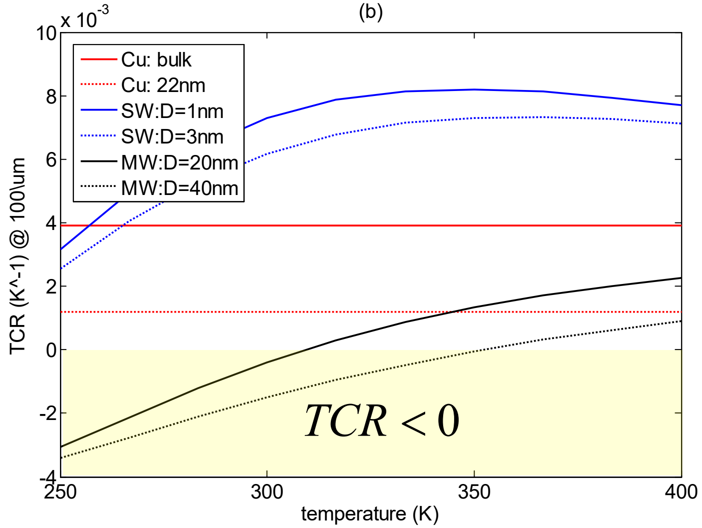
$TCR_{Cu} > 0$ **always!**

***A. Maffucci et al.*, IEEE T. CPMT, 2017**

T=300K, Rp=100kΩ




*len*=100 μm, Rp=100kΩ



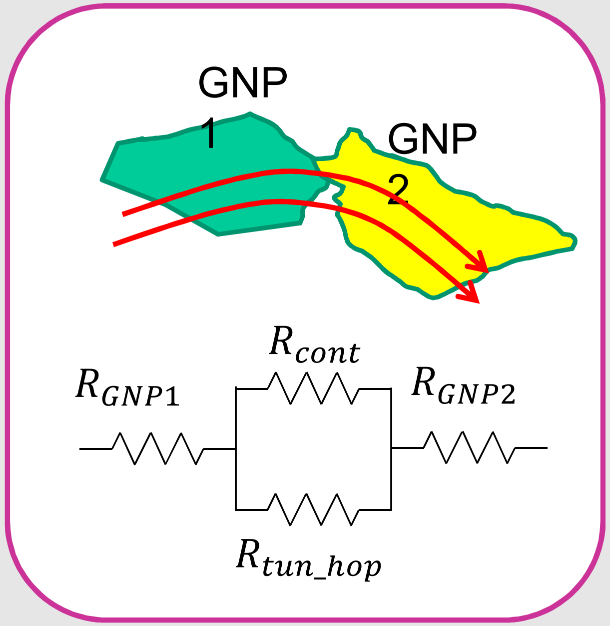
# Modelling the electrical resistivity vs temperature: graphene nanoplatelets

Electrical **conduction along a single GNP**:

- equivalent resistance of a GNP: $R_{GNP}(T) = \dfrac{r_0}{l_{mfp}(T)M(T)} len_{GNP}$

Electrical **conduction between two adjacent GNPs**:

- resistance due to the contact, $R_{cont}(T)$
- resistance due to tunneling and hopping, $R_{tun\_hop}(T)$




$l_{mfp}$ decreases as $T^{-2}$ [1]

$M$ increases as $T$ [1]

$R_{cont}$ increases as $T$ [1]

$R_{tun\_hop}$ decreases as $T^{-1/4}$ [2]

The counteracting behavior of these parameters may lead to **any sign for TCR**

*[1] A. Maffucci et al.,* IEEE T. CPMT, 2017

*[2] S. Zhao et al.,* Journal of Materials Chemistry C, 2017

Electro-thermal applications

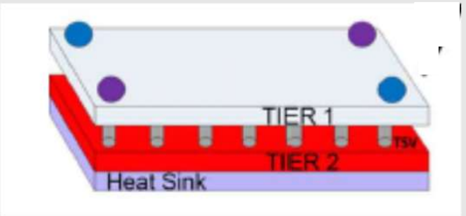
Electro-thermal modelling

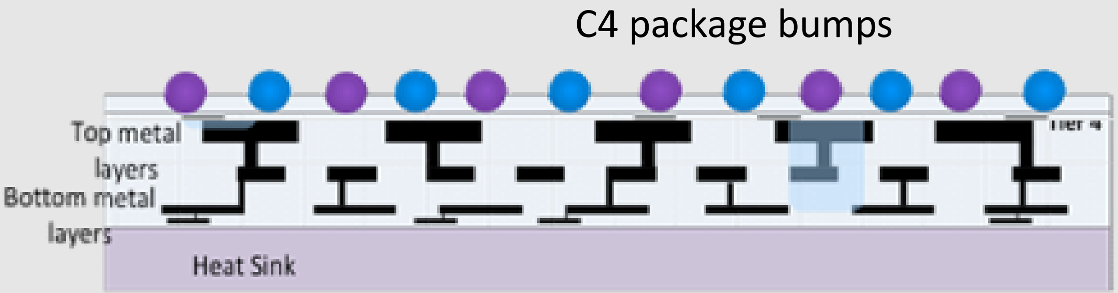
**Simulation and characterization evidence**

- **Power Delivery Networs**
- **RRAM**
- **Sensors**
- **Heaters**

Carbon-based materials for electro-thermal applications

# Electro-thermal modelling of a large PDN with the reduced-order technique (clustering)




**A 1-tier PDN (45 nm node)**

Power is fed from package through C4 bumps and distributed over the PDN

The GND grid is connected to a heat sink

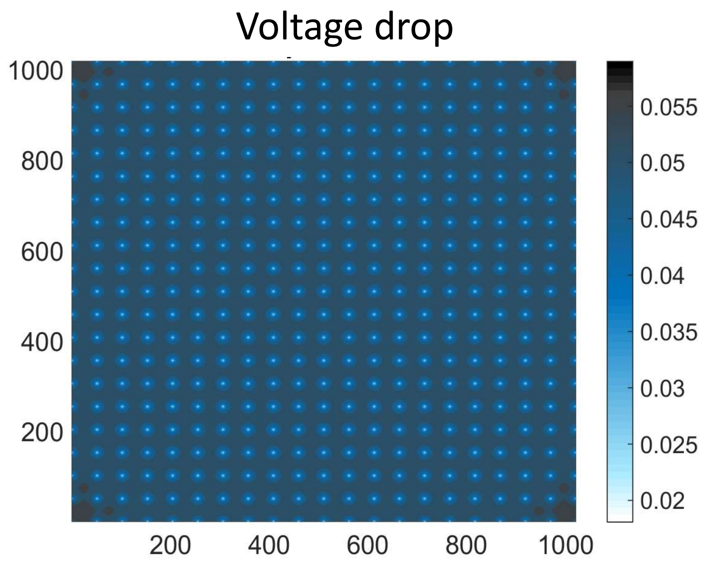
We assume a single core of 20 x 20 mm, with power density 1.5 μW/μm$^2$

Typical values of parameters for a PDN of 45nm technology (from ITRS)

| Thermal parameters | | |
|---|---|---|
| $R_{TH}$ [kK/W] | $R_{HS}$ [MK/W] | $T_0$ [°C] |
| 8.473 | 0.8437 | 27 |

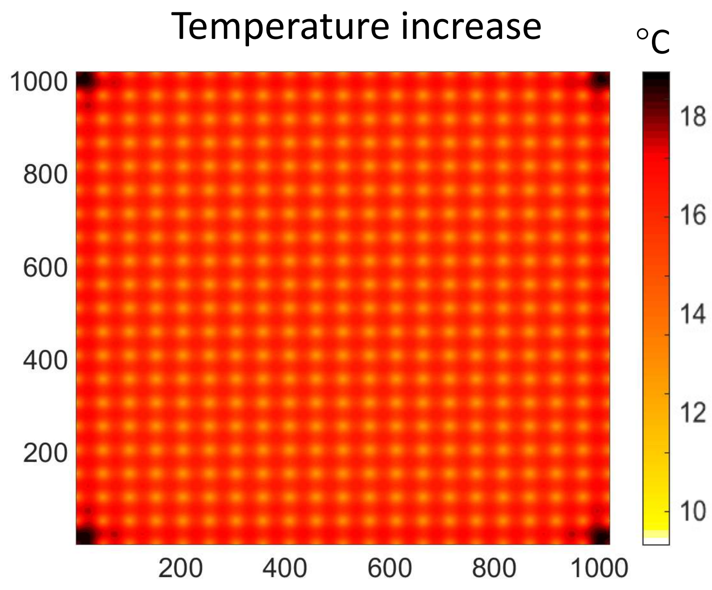
| Electrical parameters | | | | |
|---|---|---|---|---|
| $V_{DD}$ [V] | $C_0$ [aF] | $I_0$ [mA] | $R_{PKG}$ [Ω] | $R_S$ [Ω] |
| 1.0 | 4.08 | 0.1 | 0.01 | 0.056 |

# Electro-thermal modelling of a large PDN with the reduced-order technique (clustering)




**Original**: **1.040.400 nodes** per layer

**Reduced**: **300 nodes** per layer




| Clustering threshold |
| --- |
| $\Delta V_d = 0.74$ mV ($N_V = 55$) |

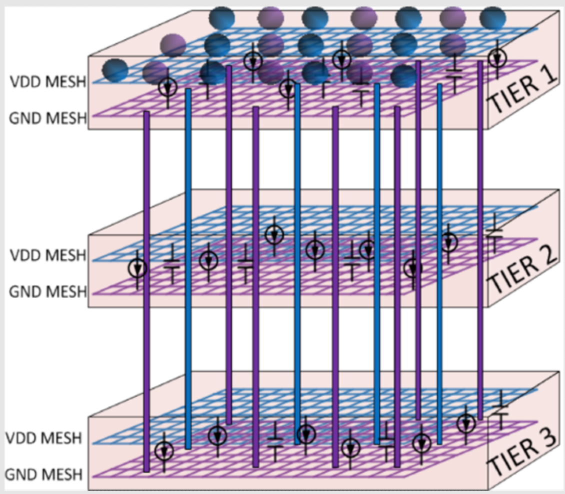
| Clustering threshold |
| --- |
| $\Delta T_r = 0.32$ K ($N_T = 77$) |

| Accuracy | |
| --- | --- |
| Maximum error on voltage drop | < 0.4 % |

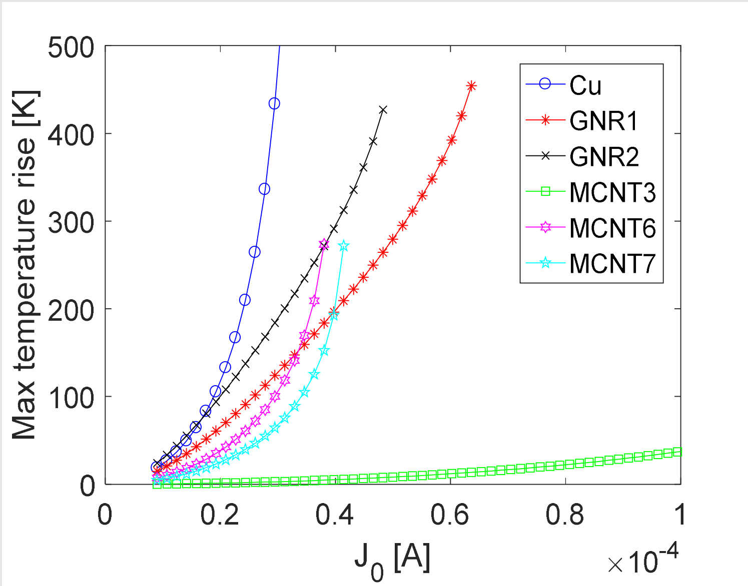
| Accuracy | |
| --- | --- |
| Maximum error on temperature | < 2.5 % |

# Power integrity analysis for carbon-based PDNs

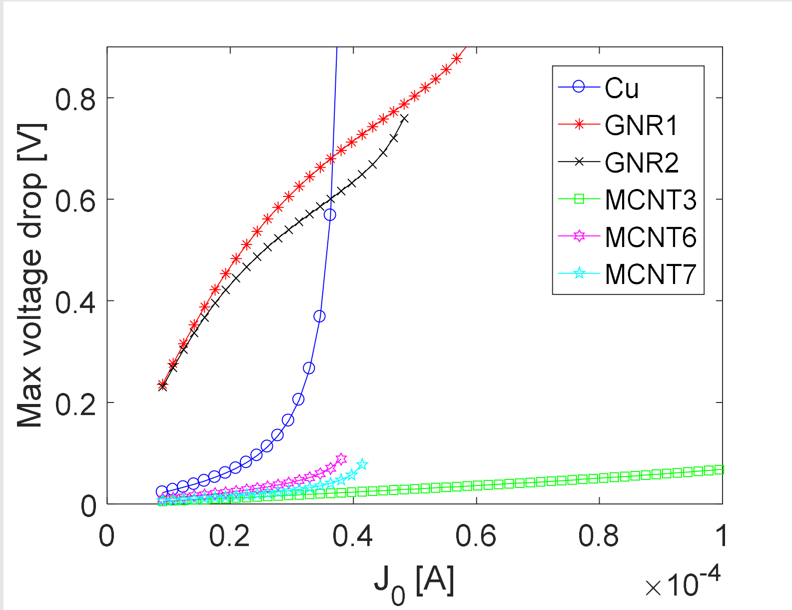
**A 3-tier PDN**




**Max Temperature rise (K)**




**Max Voltage drop (V)**

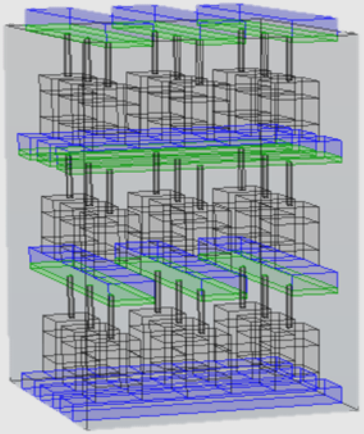



**Outstanding stability of power delivery networks made by multi-walled CNTs**

*A. Maffucci, A. Magnani, M. de Magistris, A. Todri-Sanial,* **IEEE T-NANO, 2016**

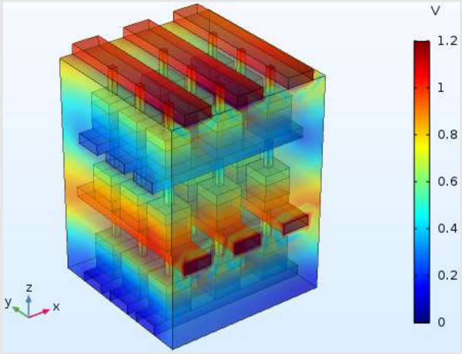
# Signal and thermal integrity analysis

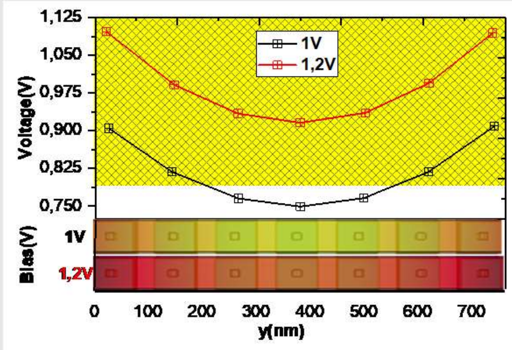
**RRAM X-bar**

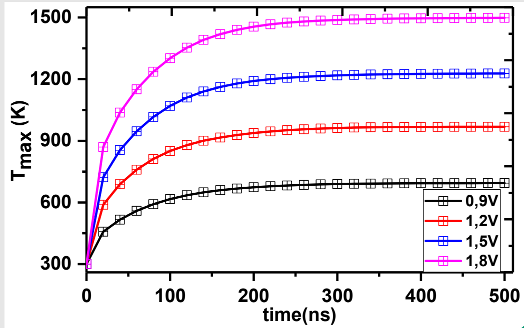


**Voltage distribution** | **Voltage drop (V)** | **Temperature rise (K)**

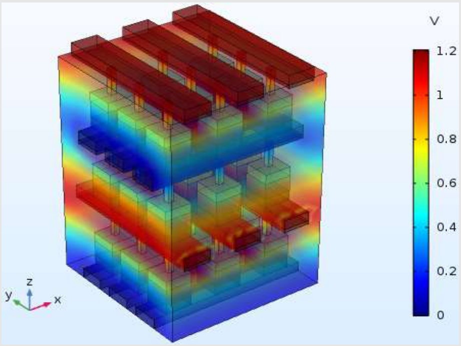
**Nickel bars**

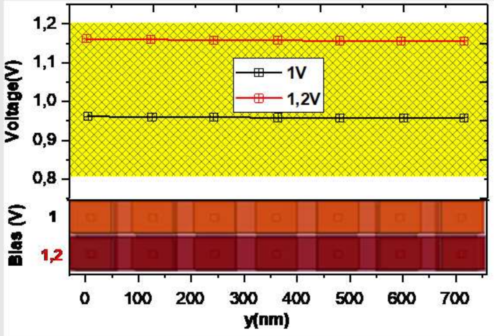


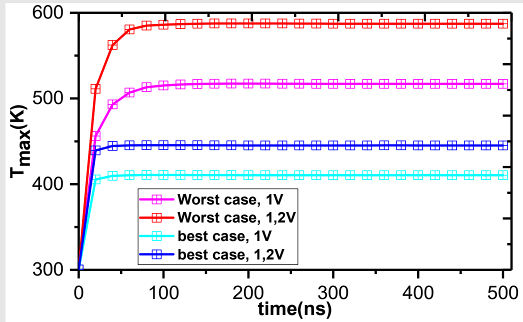



**CNT bars**

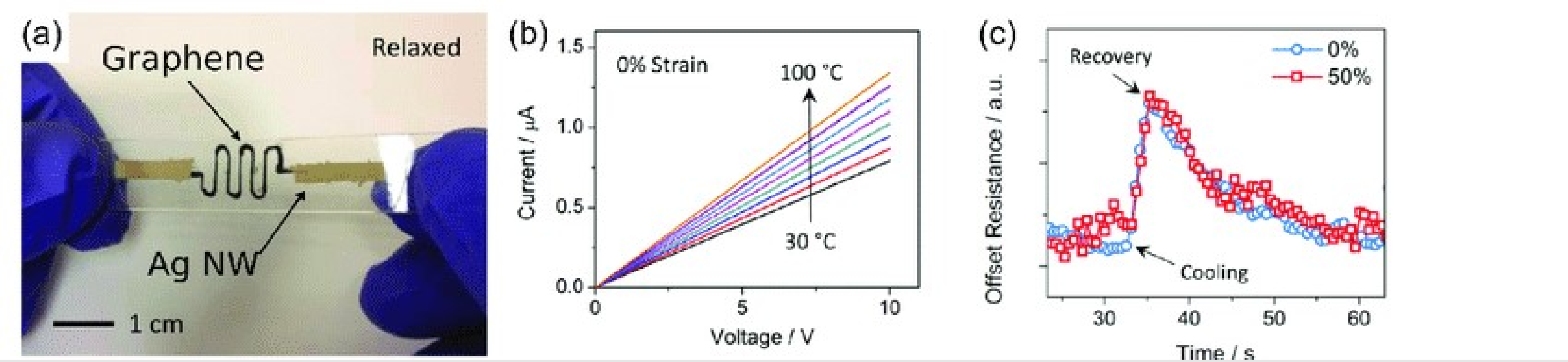





*F. Zayer, et al.,* IEEE Trans. Electron Devices, 2021

# Graphene sensors (thermristors)




**Flexible wearable temperature sensors:**

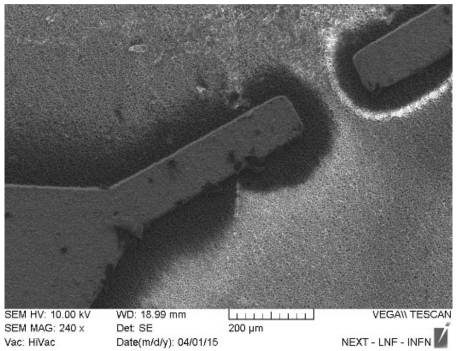
(a) stretchable graphene thermistor with AgNW (Ag nanowire) electrodes as contacts at relaxed state;
(b) its I-V curves when temperature changing from 30 to 100 °C
(c) transient response to changing temperature at 0 and 50% strains

***C. Yan, et al.***
ACS Nano 2015

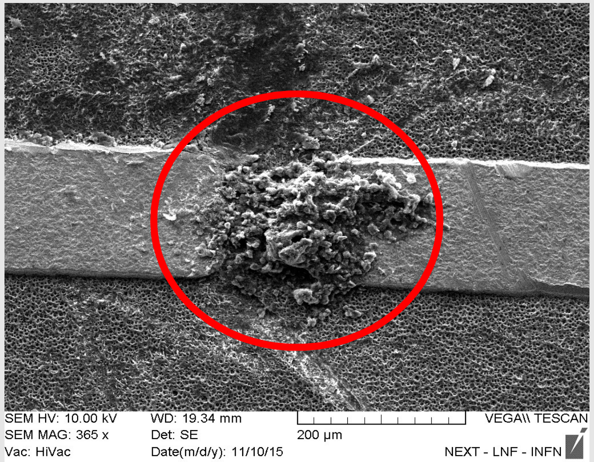
# Experimental evidence of NTC behavior: lab materials

**Device**


**Gap**

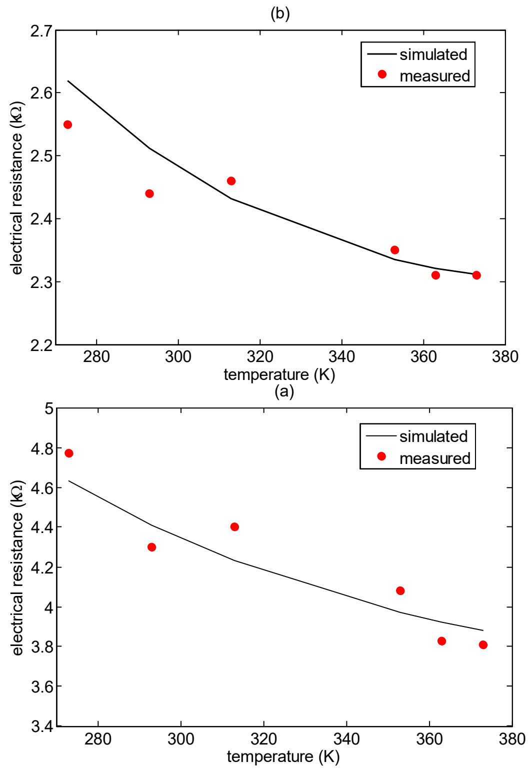



| GAP | Length L (µm) | Width W (µm) |
|---|---|---|
| **Device 1** | 150 | 150 |
| **Device 2** | 100 | 150 |
| **Device 3** | 150 | 100 |
| **Device 4** | 100 | 100 |




**Realized CNT contact**

**Resistance vs temperature**



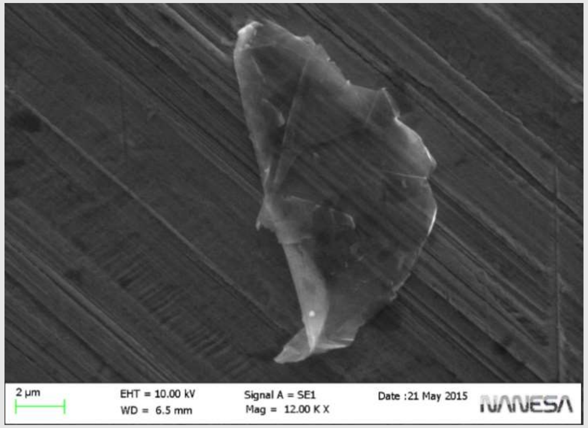

***A. Maffucci, F. Micciulla, A. Cataldo, G. Miano, S. Bellucci,*** IEEE Tran. on CPMT, 2017.

# Experimental evidence of NTC behavior: industrial material

1) **GNP production:** from graphite, by liquid exfoliation technology
2) **mixture formulation**: GNP particles are dispersed in solvent and sonicated with a polymeric binder
3) **spray deposition**: the mixture is sprayed at a controlled pressure, by using a semiautomatic 3-axes pantograph.
4) **calendering**: in order to obtain a compact sheet and optimize the final thickness/alignment ratio for each material

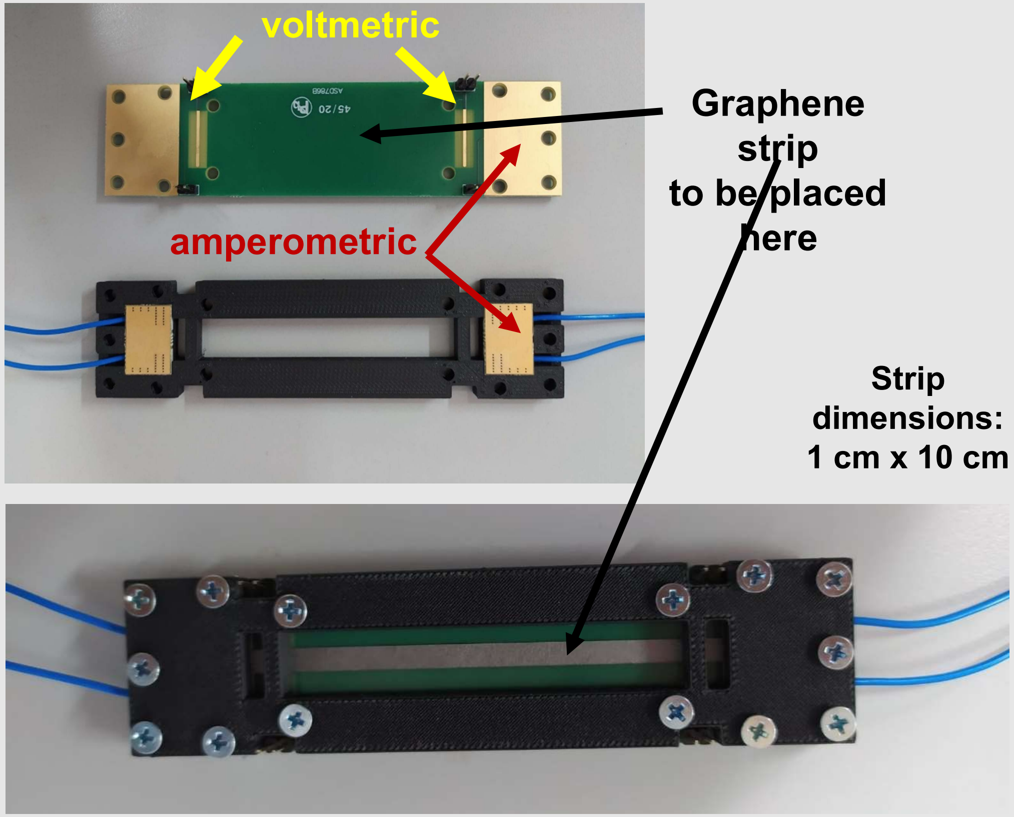
**MATERIALS ANALYZED HERE**:

| Material | GNPs (%) | Binder (type) | Thickness (µm) | Width (mm) | Length (mm) |
|---|---|---|---|---|---|
| G-Paper | 100 | --- | 55 | 10 | 180 |
| G-PREG (95/5) | 95 | polyurethane | 75 | 10 | 180 |
| G-PREG (70/30) | 70 | epoxy | 75 | 10 | 180 |

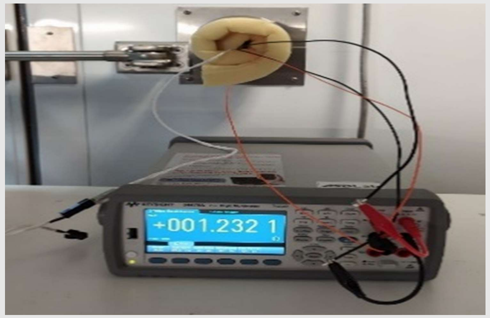


# Experimental evidence of NTC behavior: graphene strip characterization

## Ad-hoc test fixture

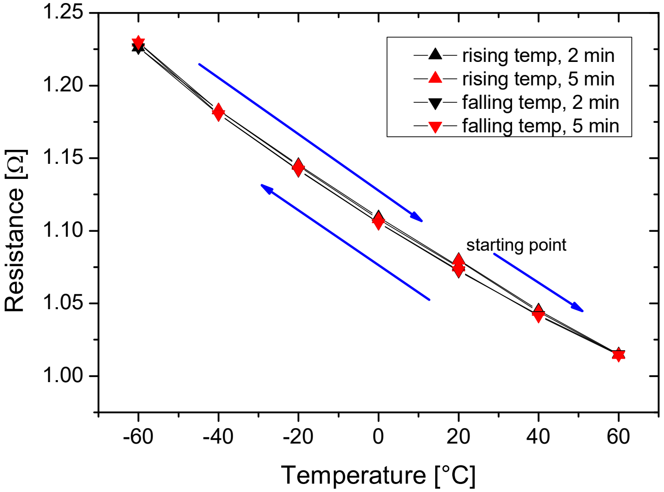



## Climatic chamber test

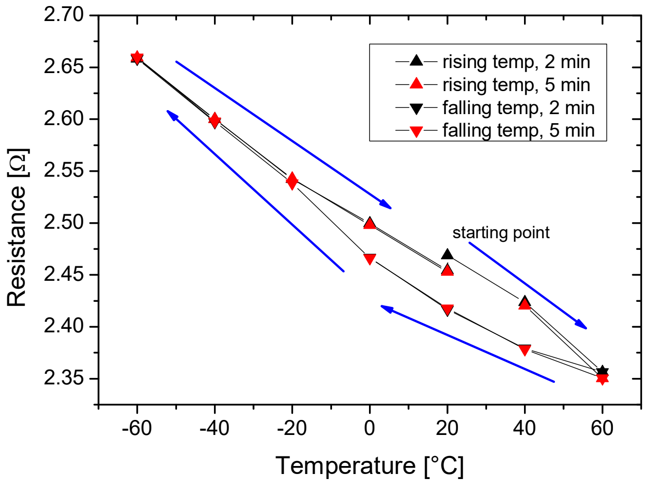



# Experimental evidence of NTC behavior: graphene strip characterization

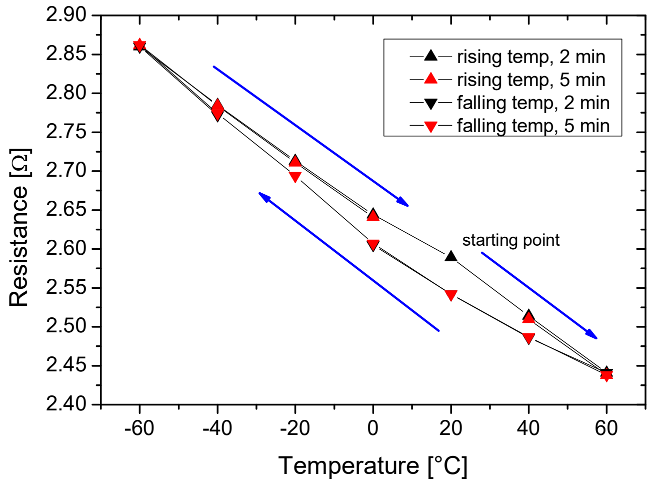
**G-paper**




**G-Preg (95/5)**




**G-Preg (70/30)**




The electrical resistance is a **decreasing function** of the temperature for all materials (NTC materials)

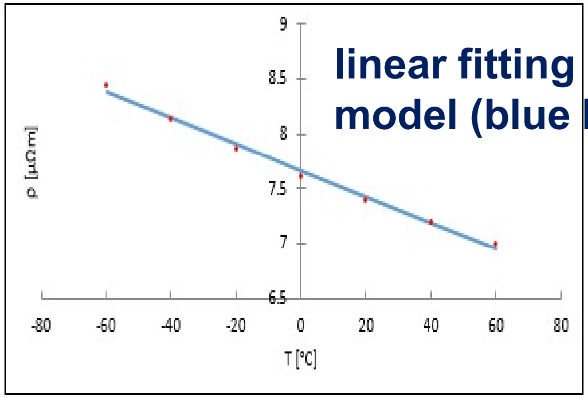
A modest effect of **hysteresis** can be observed for the composite materials, with a maximum difference of about 2% for G-Preg (95/5) and 3% for G-Preg (70/30)

# Linear model for the equivalent resistivity

Linear approximation $\rho(T) = \rho_0[1 + \beta(T - T_0)]$

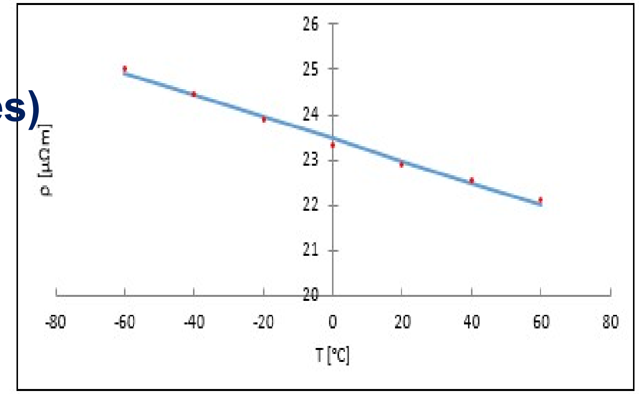
The same model as for conventional conductors

**G-paper**

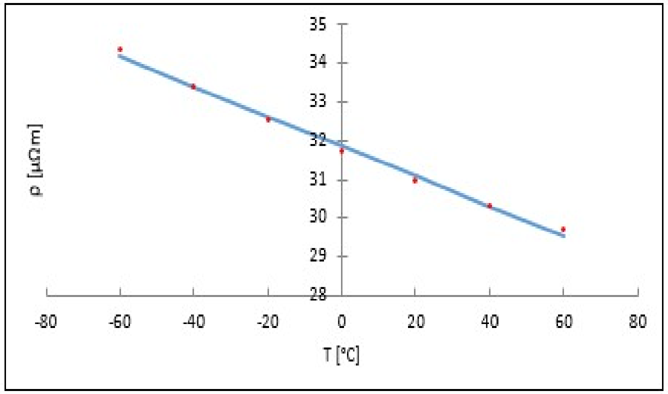



**linear fitting model (blue lines)**

**G-Preg (95/5)**




**G-Preg (70/30)**




| $T_0$ = 20 °C | Cu (bulk) | G-paper | G-Preg (95/5) | G-Preg (70/30) |
|---|---|---|---|---|
| $\rho_0$ $(10^{-8}\ \Omega\text{m})$ | 1.68 | 747 | 2295 | 3095 |
| $\beta$ ($K^{-1}$) | 0.0039 | -0.0016 | -0.0010 | -0.012 |

*S. Sibilia, et al., A. Maffucci,*
**Nanotechnology, 2021**

## Conclusions

- The **electro-thermal** behavior of materials may lead to **issues** (heat problems in integrated circuits) but also to **opportunities** (thermristors as sensors, thermal-enabled memristors)
- To overcome the present limits and to catch the foreseen opportunities, novel nano-materials based on carbon **are proposed, due to their excellent electrical and thermal properties**
- Carbon nanotube interconnects and graphene thermal material interfaces are predicted to dramatically **mitigate the issues** related to heat management in integrated circuits
- **Industrial graphene** (such as graphene nanoplatelets), with poorer quality, is still a valid choice for electro-thermal applications
- GNP strips have proven to behave as a **negative temperature coefficient (NTC) material**, with a linear response in a large temperature range.


THANK YOU FOR
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