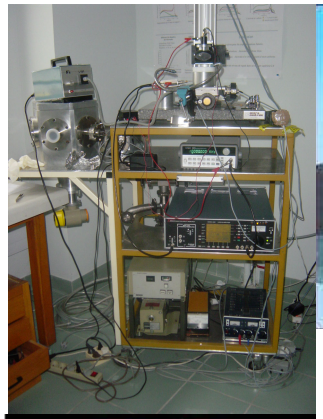

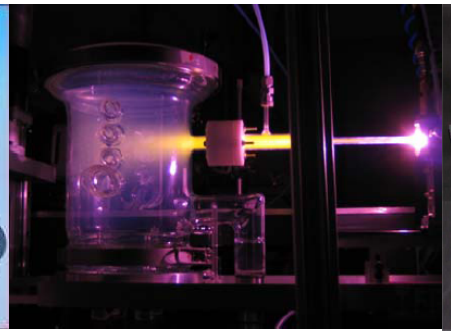

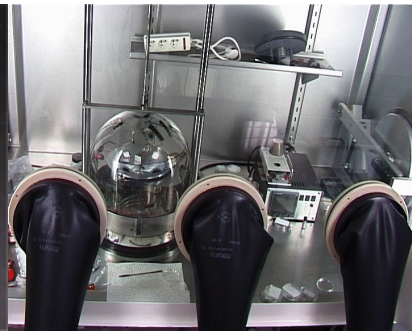
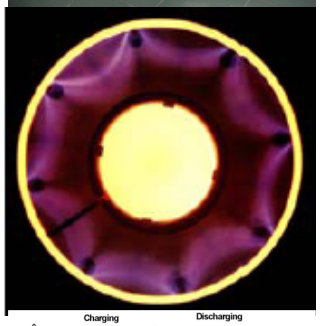
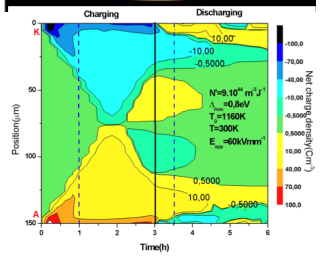

Ceramic substrates for high voltage power electronics: Past, present and future

Zarel VALDEZ-NAVA[1*], Driss Kenfaui[1], Marie-Laure Locatelli [1], Lionel Laudebat [1], Sophie Guillemet [2]

[1] LAPLACE, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France.
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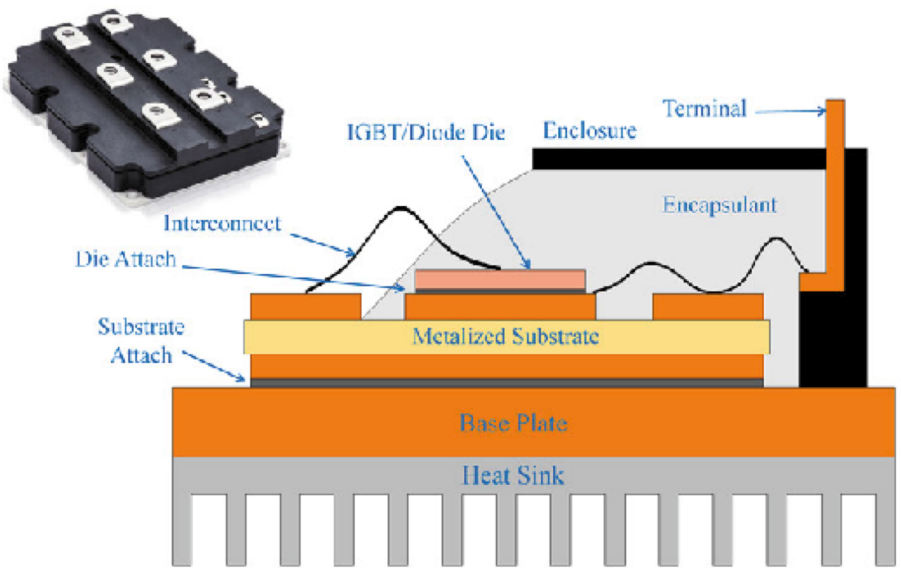
* valdez@laplace.univ-tlse.fr

IWIPP 2019, Toulouse, April 26, 2019

1. Power electronics: SC Devices & Insulation

Electrical Insulating environment of the power semiconductor die

Classical structure

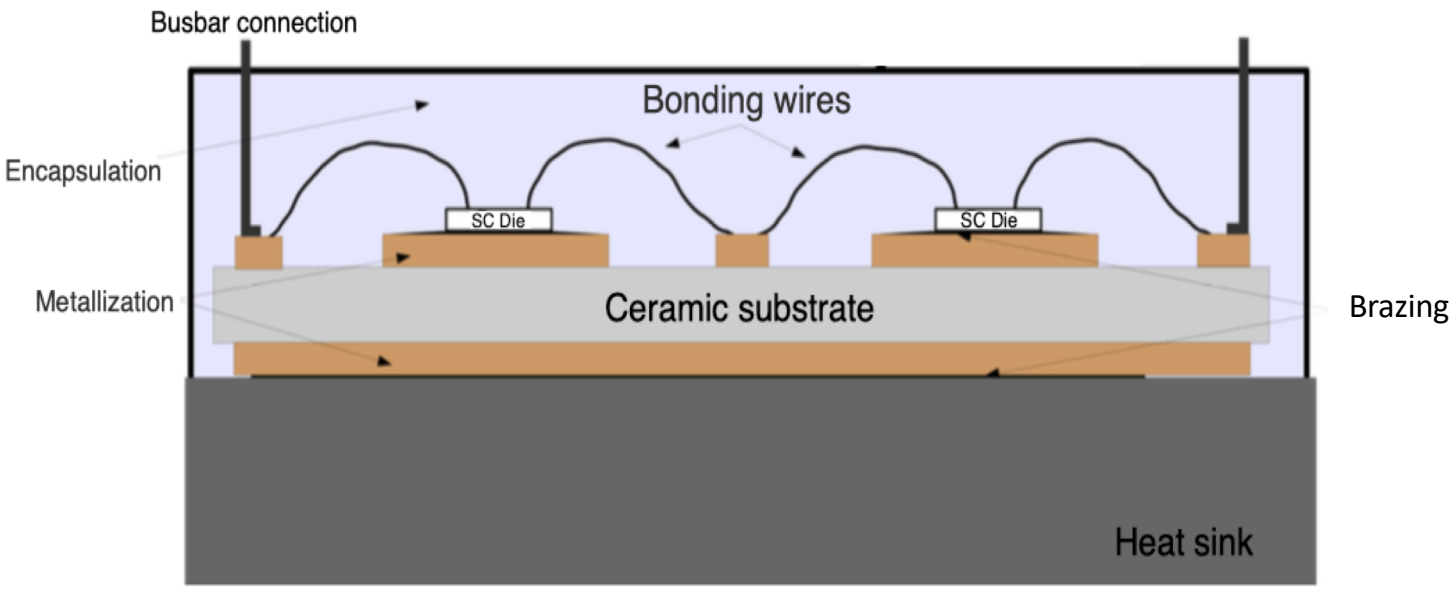


Le, VN et al. Procedia Structural Integrity, 2016, 2614-2622

=> 4 types of insulating functions :

- Insulating substrate
- Inter-metal insulation
- Semiconductor surface passivation
- Insulating filler / encapsulation

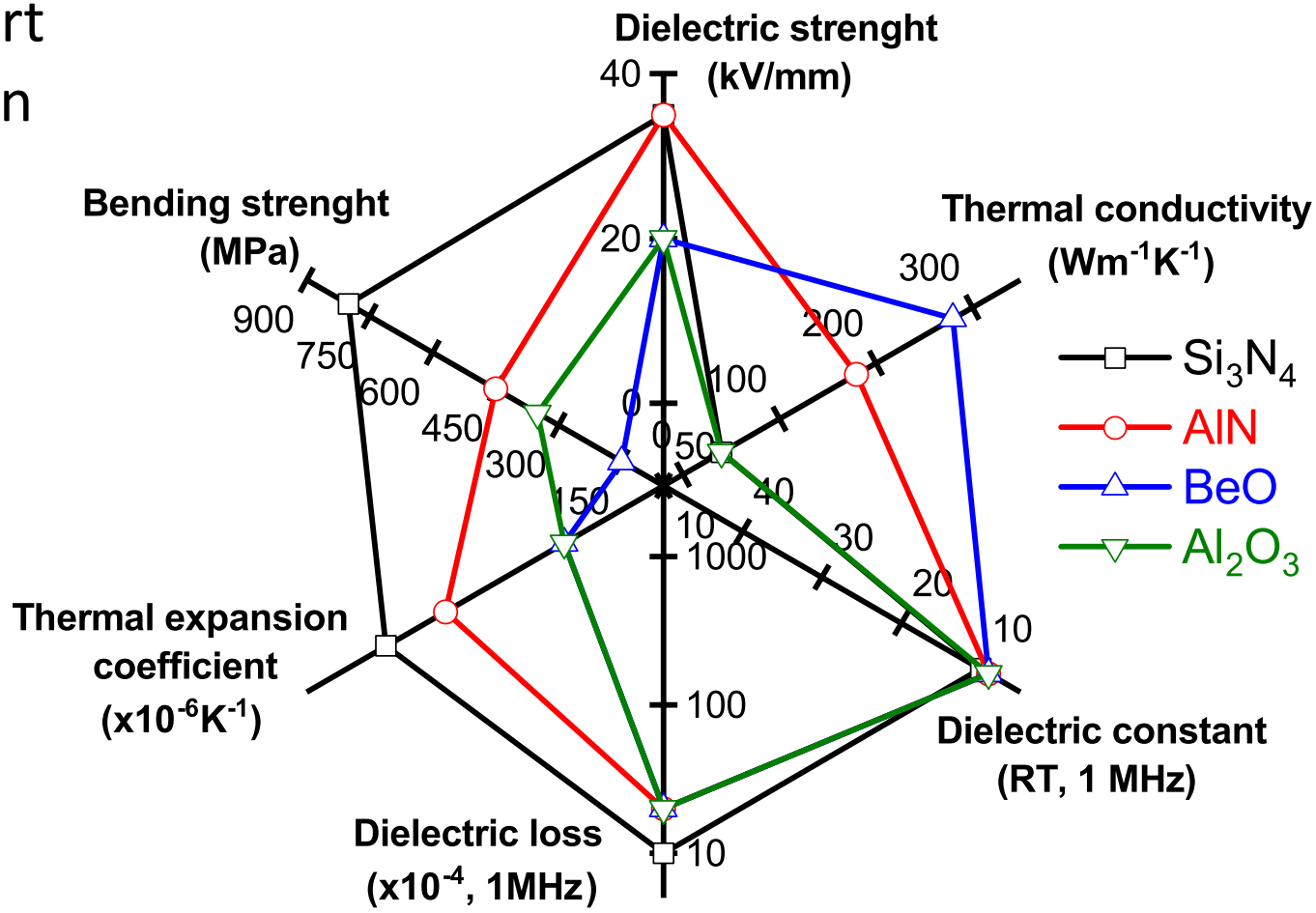
1. Power electronics: Ceramic substrate



- Thermal path
- Mechanical support
- Electrical insulation

2. Physical properties of ceramics

- Thermal path
- Mechanical support
- Electrical insulation



2. Physical properties of ceramics

- Thermal path
- Mechanical support
- Electrical insulation

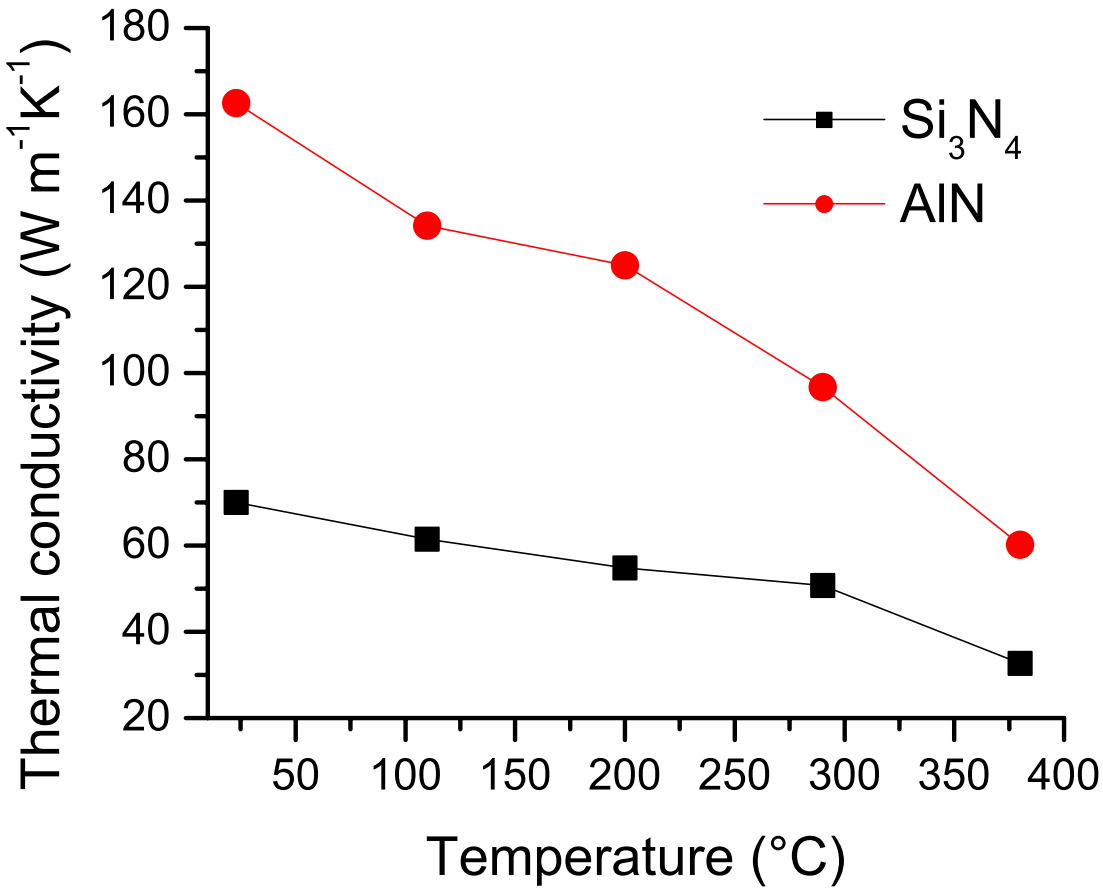
Ceramic substrate	Thermal conductivity (W/m-K) (typical values)
Al_2O_3	30-40
Si_3N_4	35-60
AlN	140-200

Aluminum nitride:

High thermal conductivity

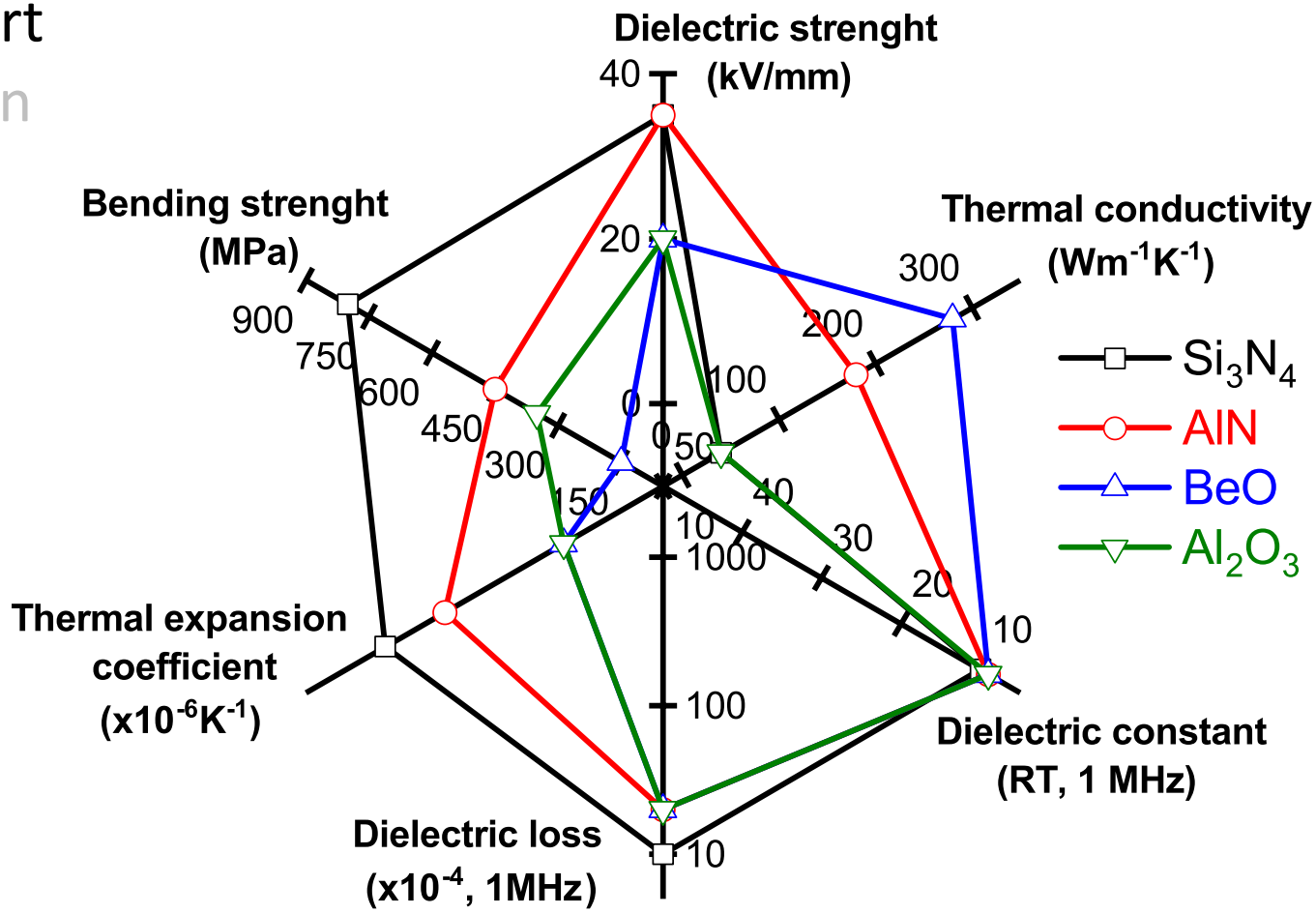
3. Dielectric properties of ceramic materials

Thermal conductivity of AlN is high, but it decreases as temperature increases



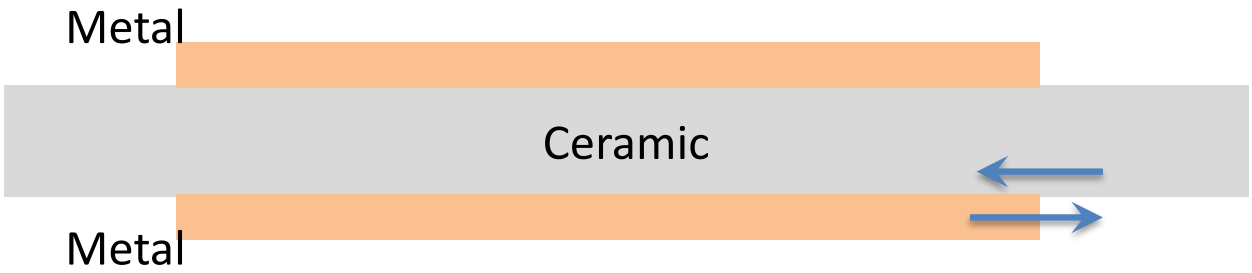
3. Physical properties of ceramics

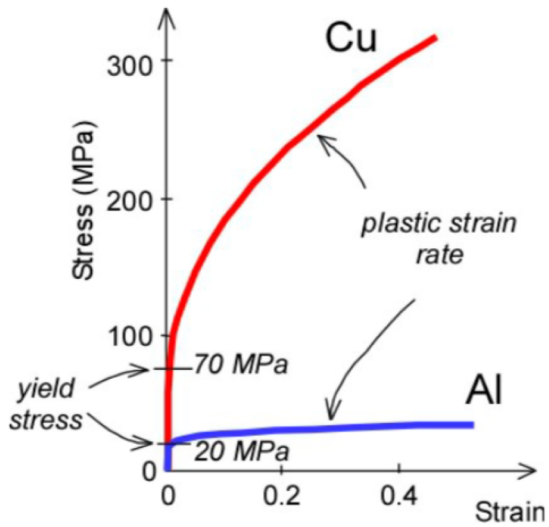
- Thermal path
- Mechanical support
- Electrical insulation



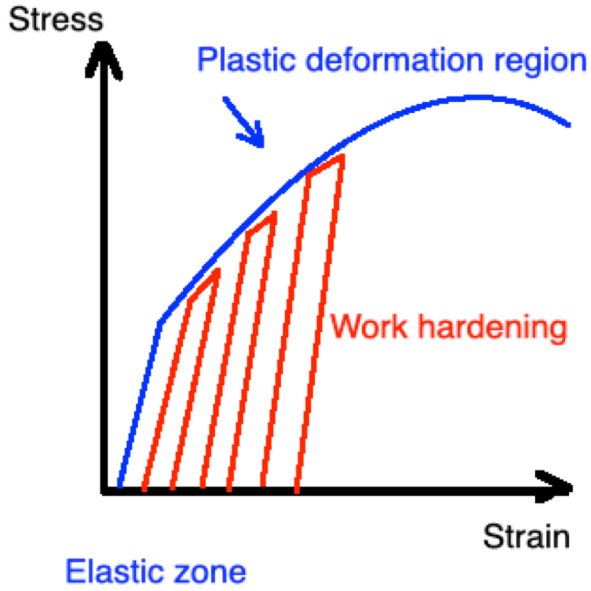
Metal-ceramic bonding

4. Mechanical failure of metallized ceramics



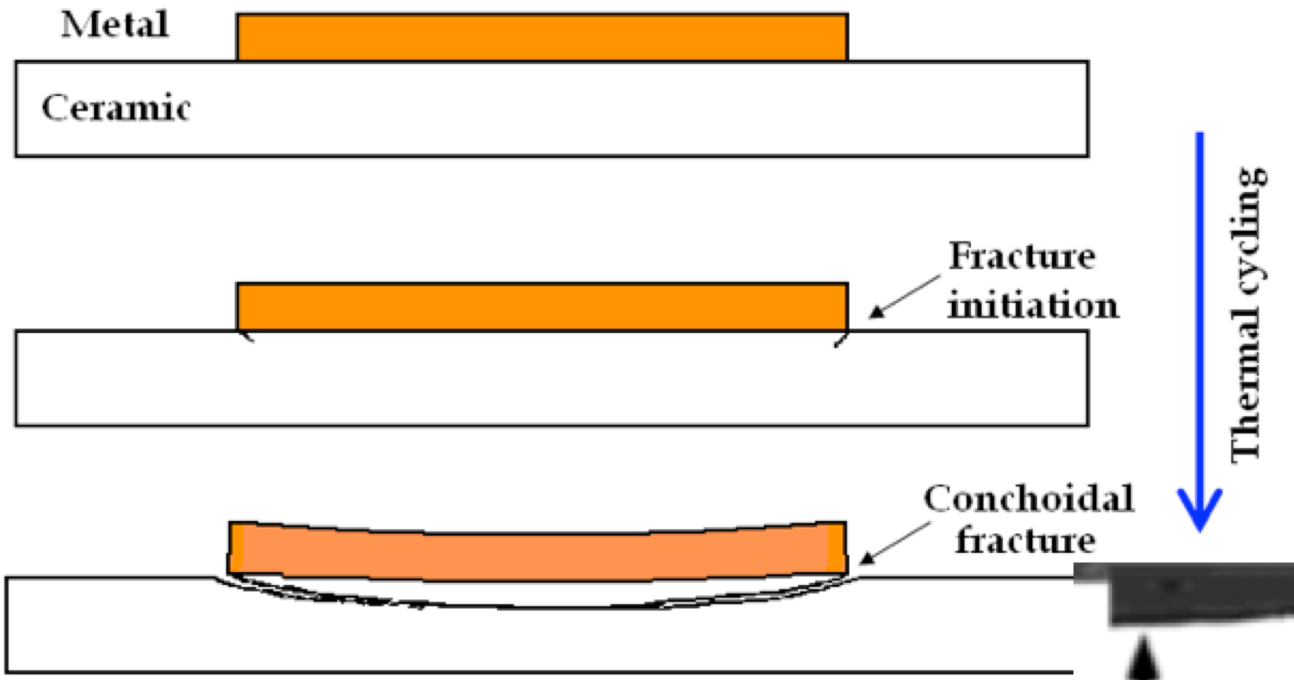


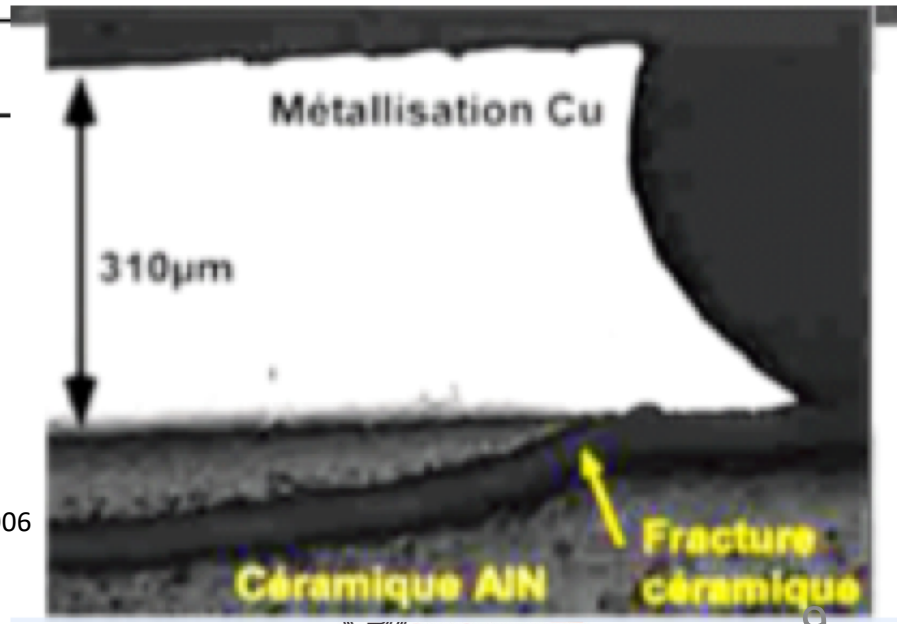
Dupont et al. Microelectronics Reliability, 2006, 1766-1771.



- Dimensions (i.e. thickness)
- Edges of metallization
- Interface
- Temperature span

4. Mechanical failure of metallized ceramics

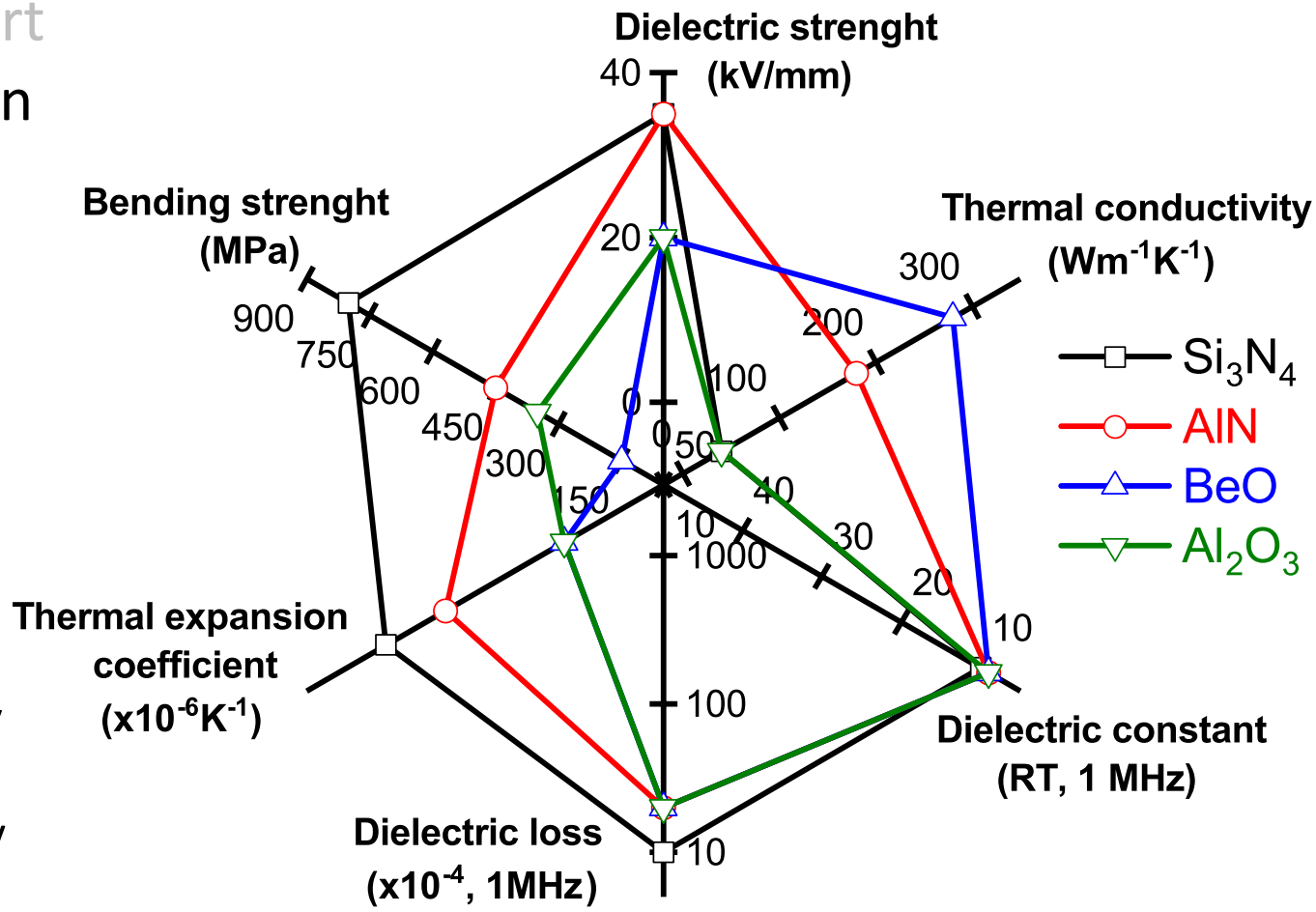




Dupont L. PhD Thesis, ENS Cachan, 2006

5. Physical properties of ceramics

- Thermal path
- Mechanical support
- Electrical insulation

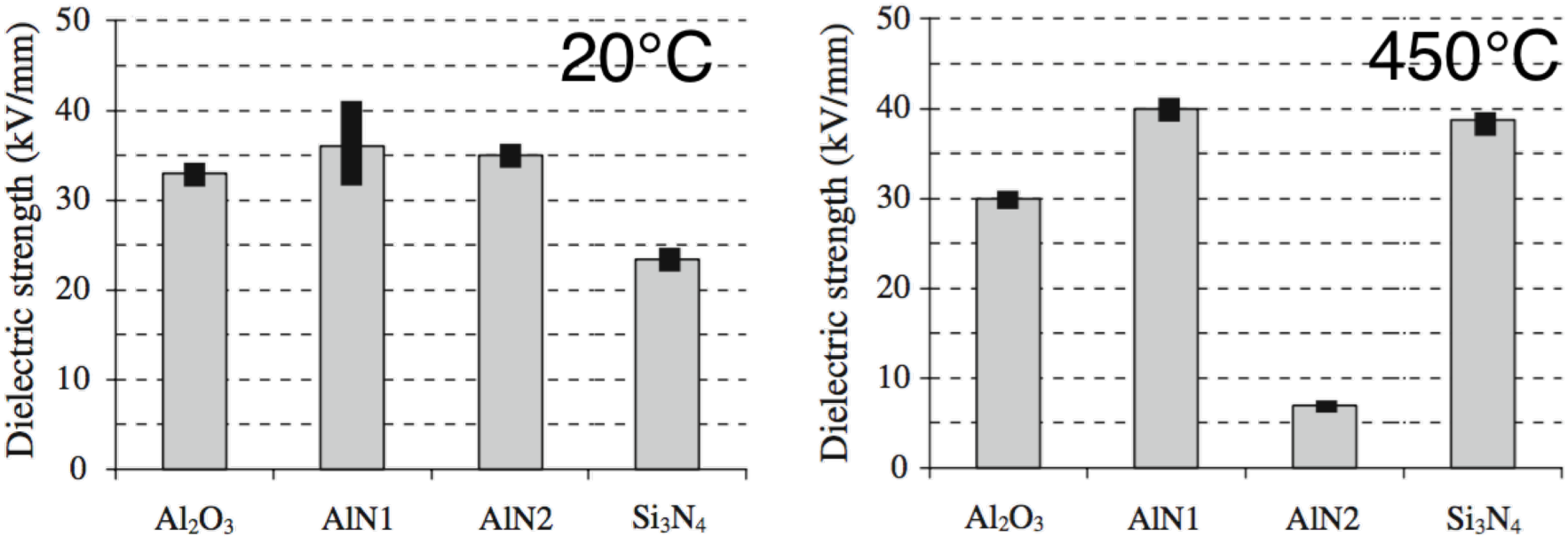


- Dielectric permittivity
- Dielectric losses
- Electrical conductivity
- Dielectric strength

5. Dielectric properties of ceramic materials

Dielectric breakdown in ceramics is dependent on:

- Material composition
- Thickness
- Temperature



Chasserio et al. Journal of Electronic Materials 38.1 (2009): 164-174.

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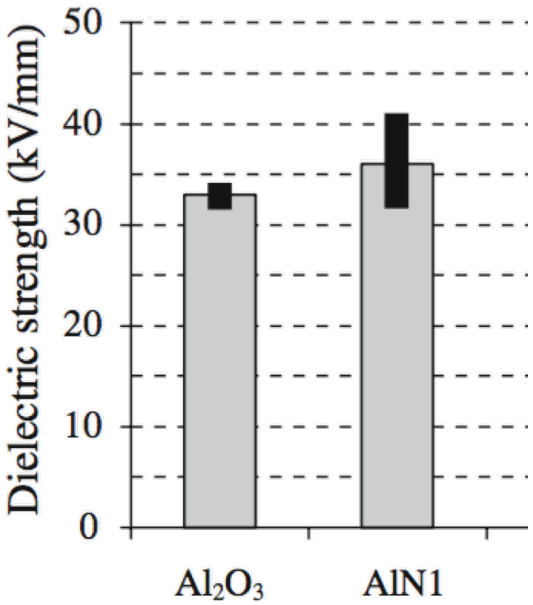

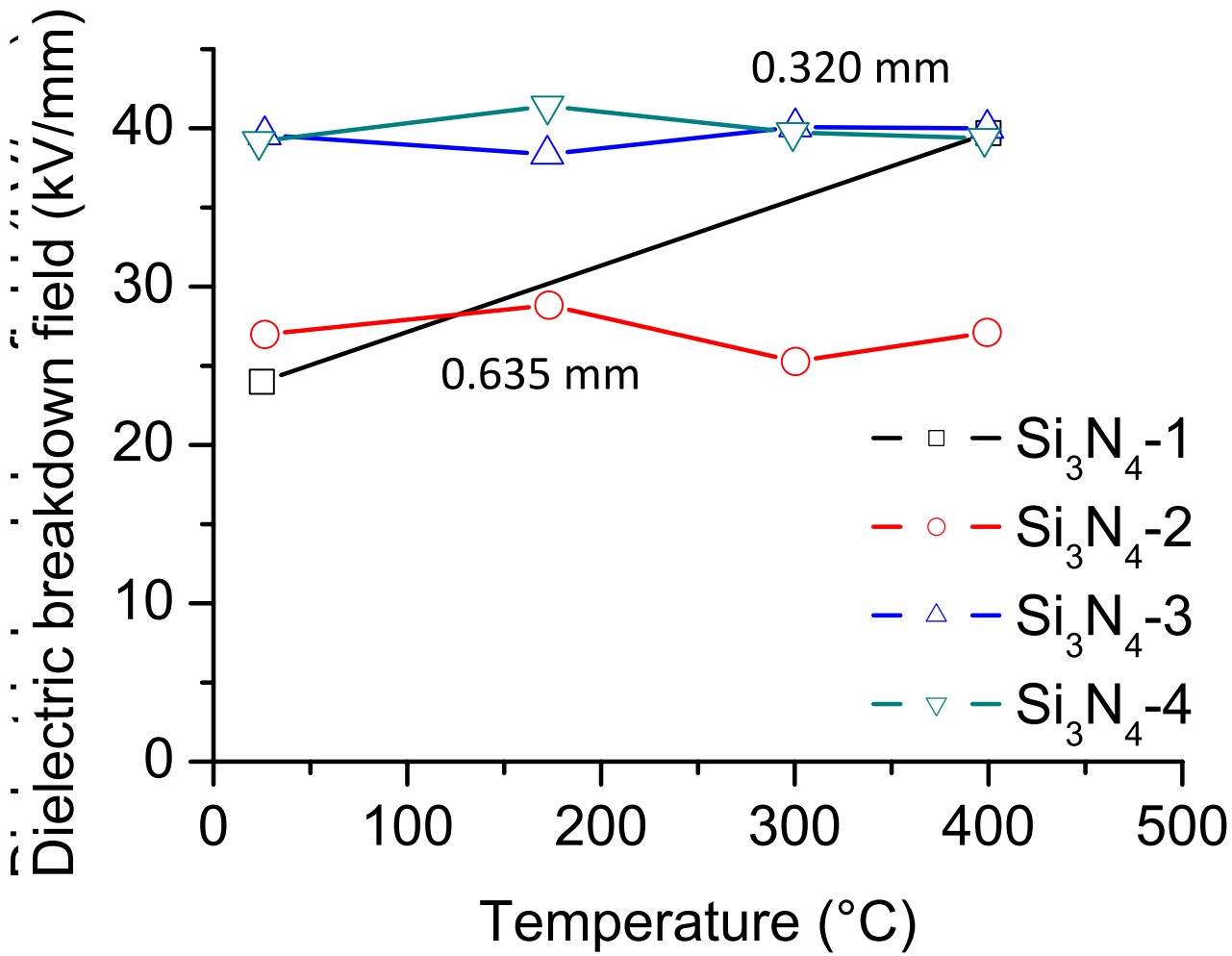

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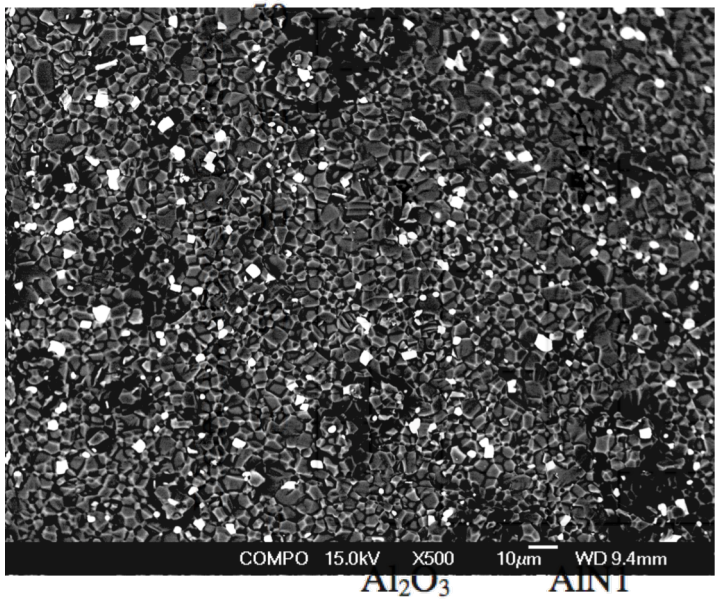

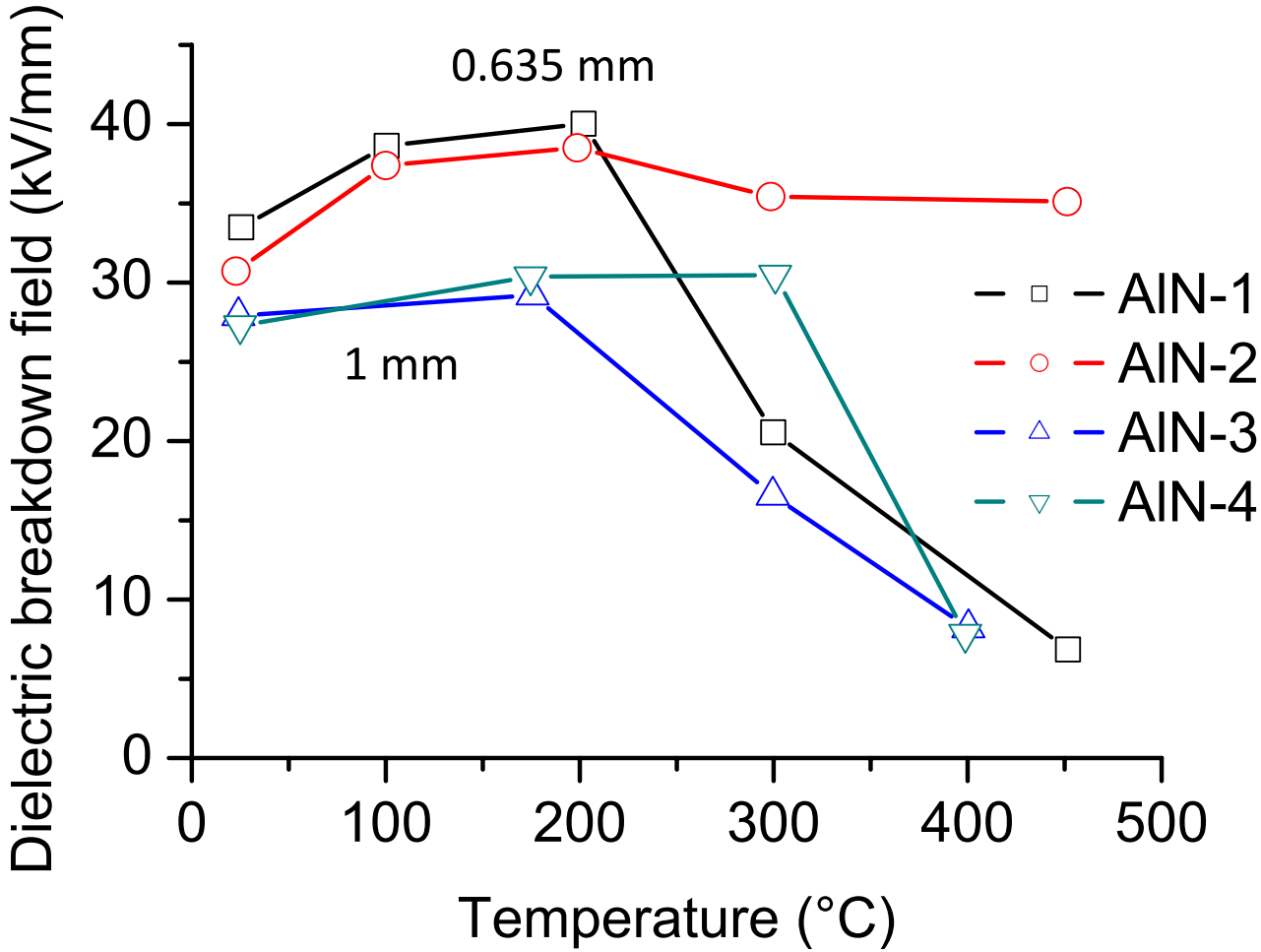

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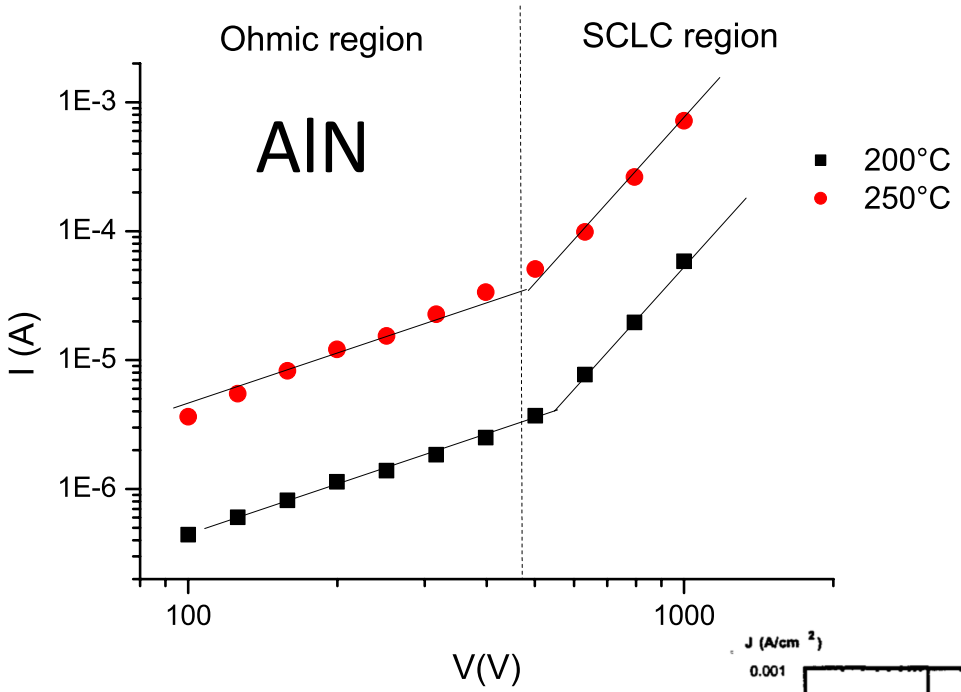
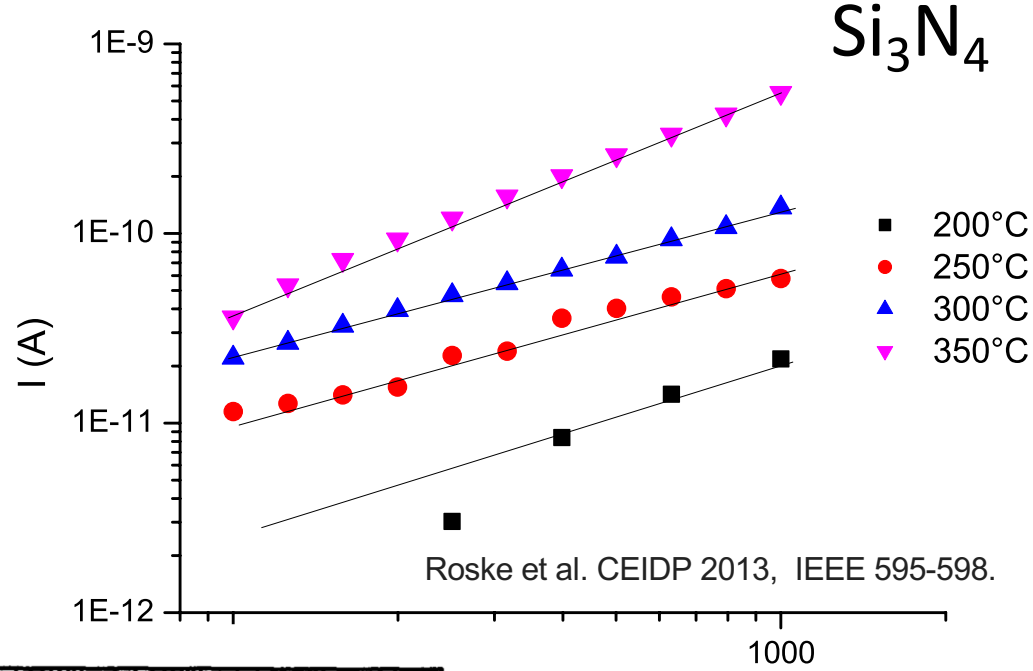
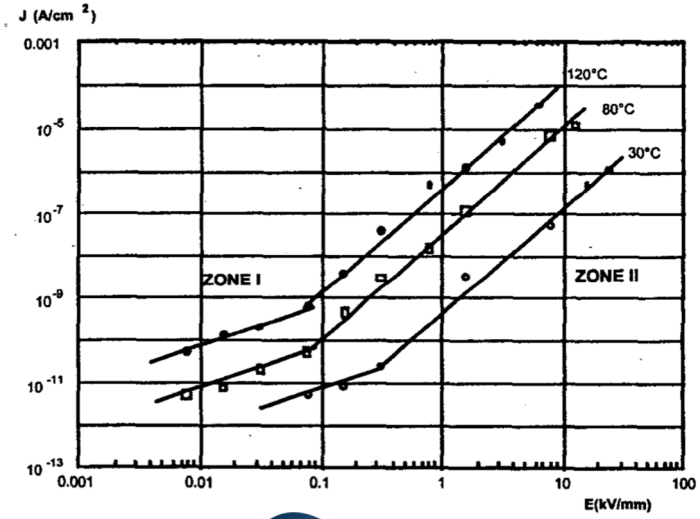




Roske et al. CEIDP 2013, IEEE 595-598.

Al_2O_3

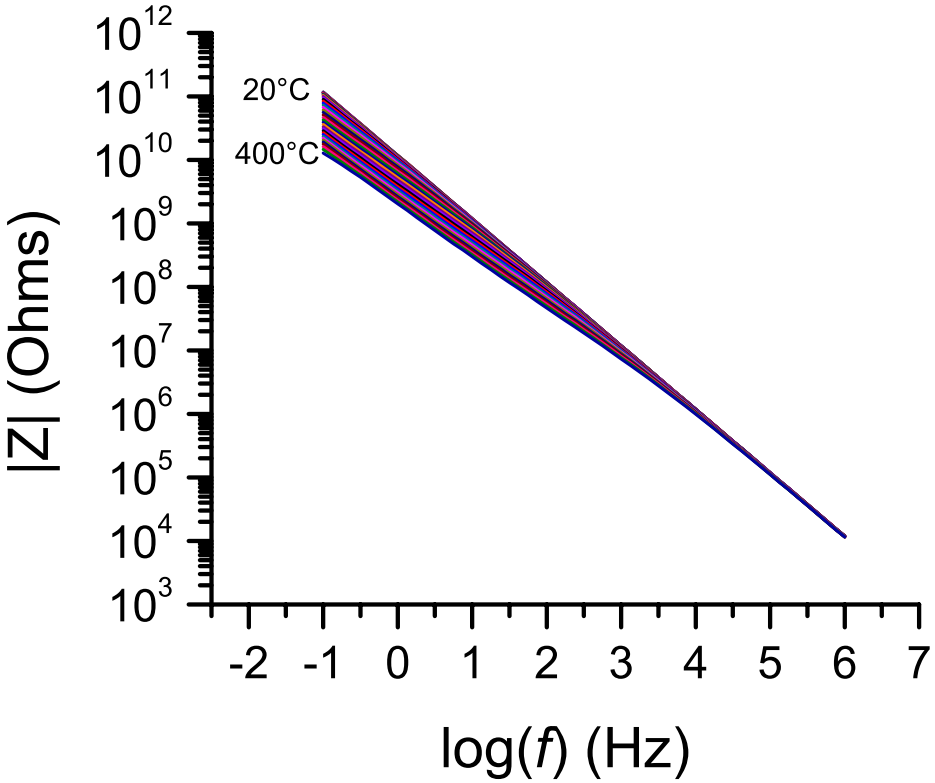


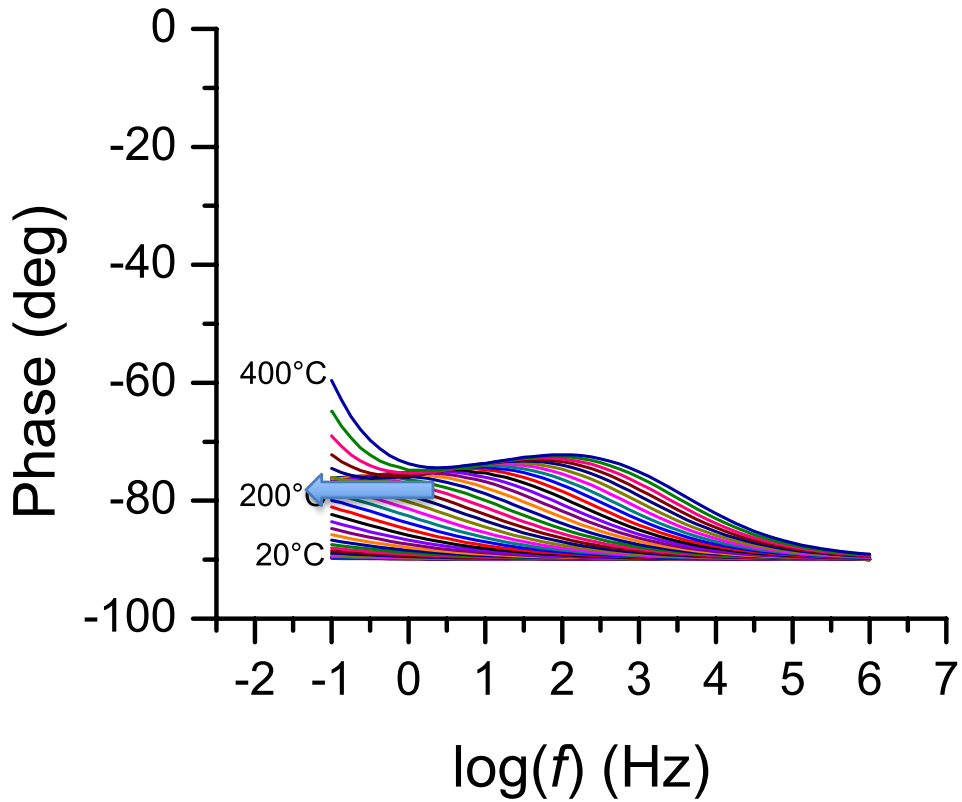
Breit, F, et al. CEIDP 2001, IEEE.

5. Dielectric properties of ceramic materials

Broadband dielectric spectroscopy

Si_3N_4

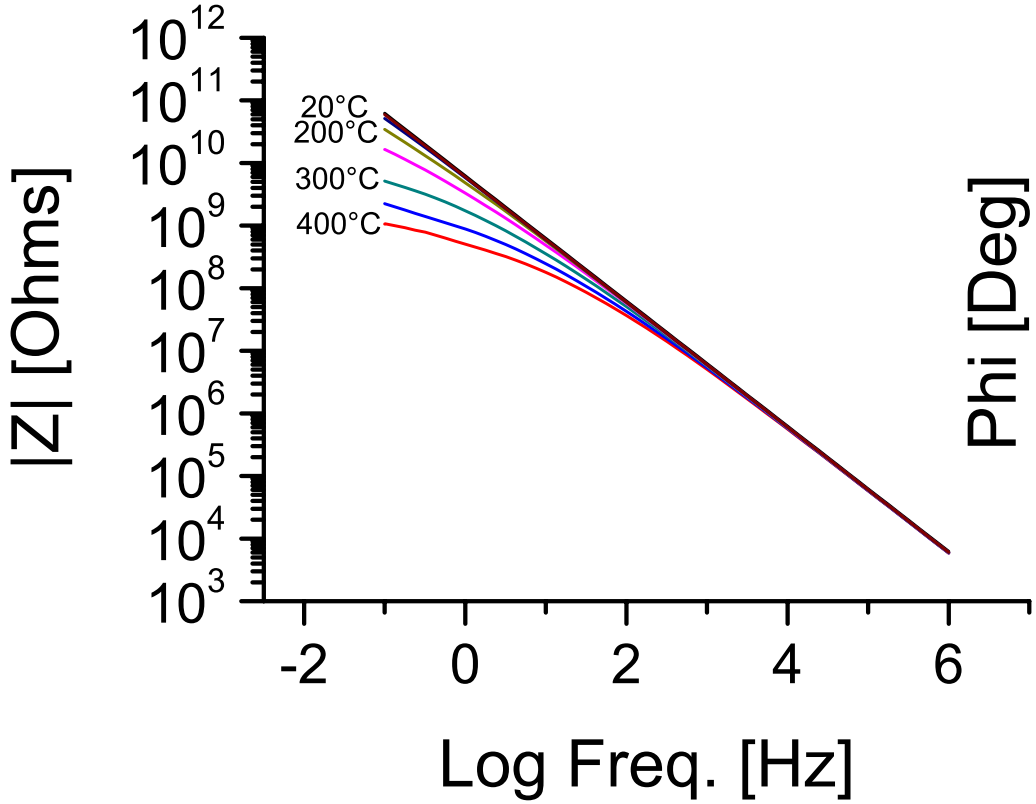


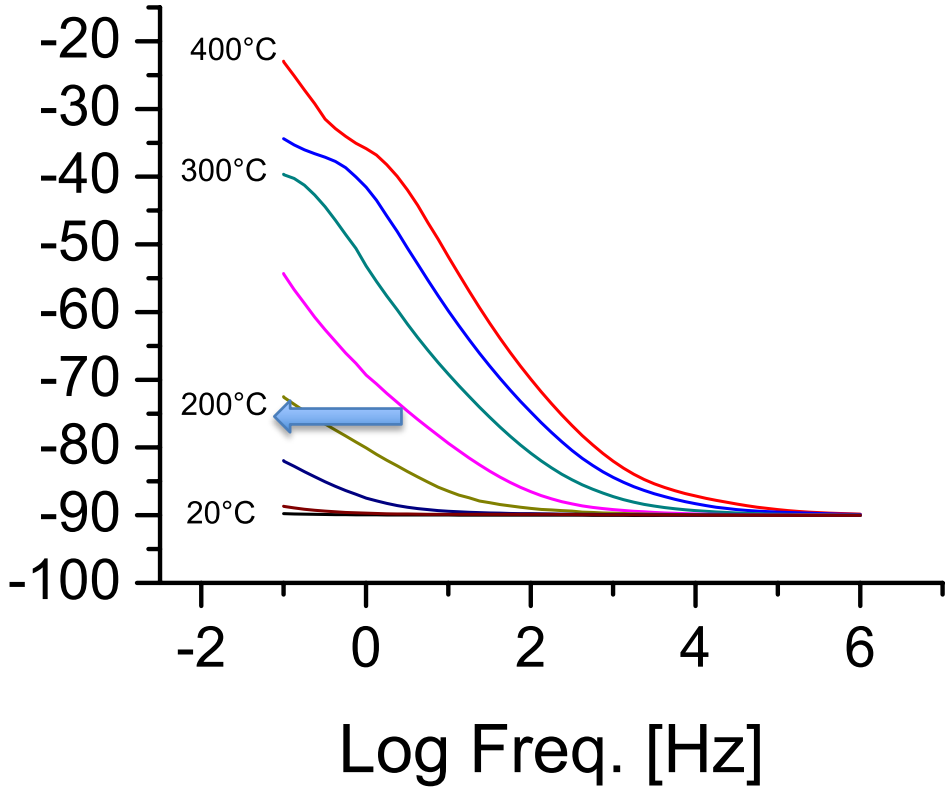


5. Dielectric properties of ceramic materials

Broadband dielectric spectroscopy

AlN





5. Dielectric properties of ceramic materials

- All dielectric properties are impacted by temperature
  - Permittivity
  - Losses
  - Conductivity

- Both AlN and Si_3N_4 keep a dielectric behavior below 200°C

5. Conclusions on the state of the art

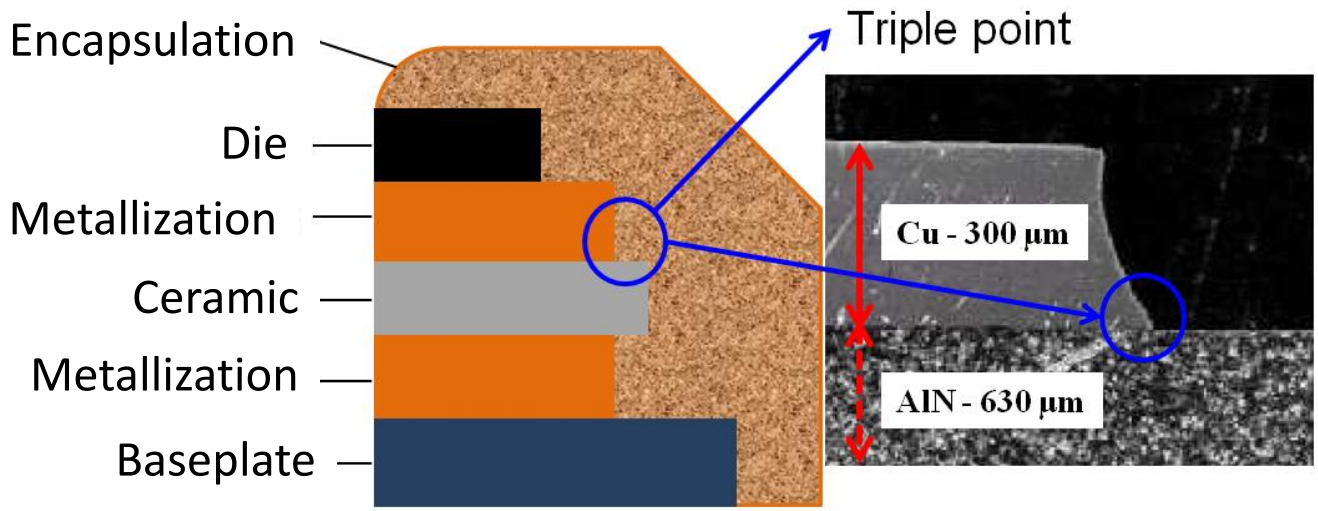
- Thermal properties
- Mechanical properties
- Dielectric properties

In current applications, with the right choices, compromises can be achieved in terms of performance and reliability

But the ceramic substrate is not alone in a power module …

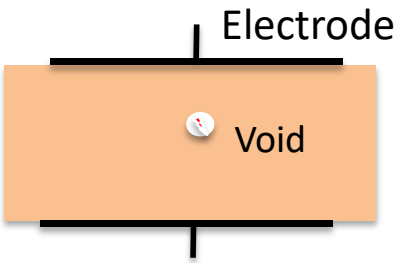
6. Impact of high dV/dt on insulation

High field at triple point



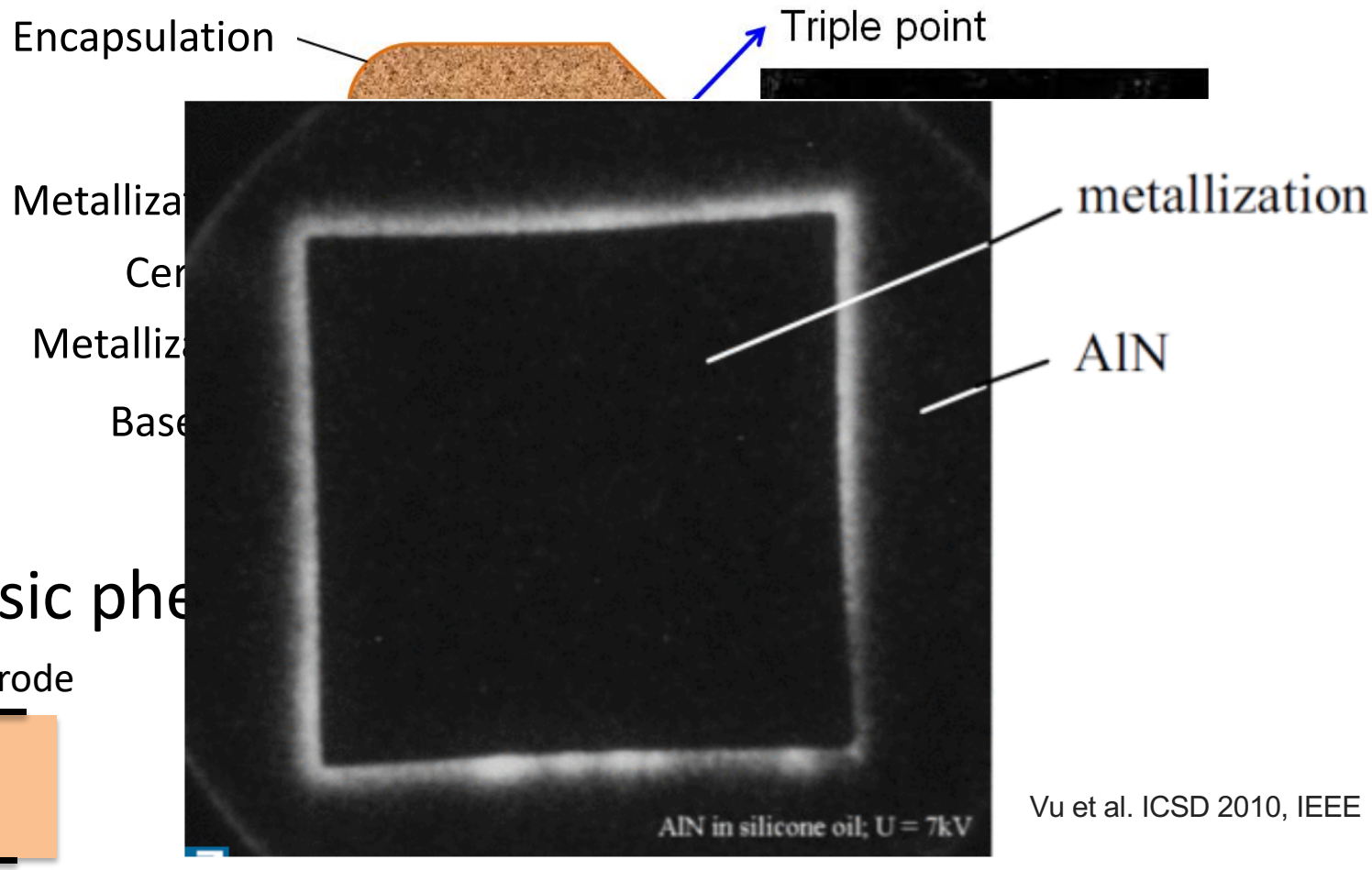
Direct bonded copper (DBC)

Extrinsic phenomena: Partial discharges



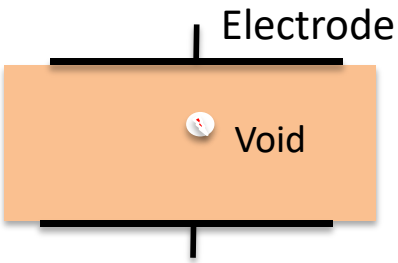
6. Impact of high dV/dt on insulation

High field at triple point



Vu et al. ICSD 2010, IEEE

Extrinsic phe



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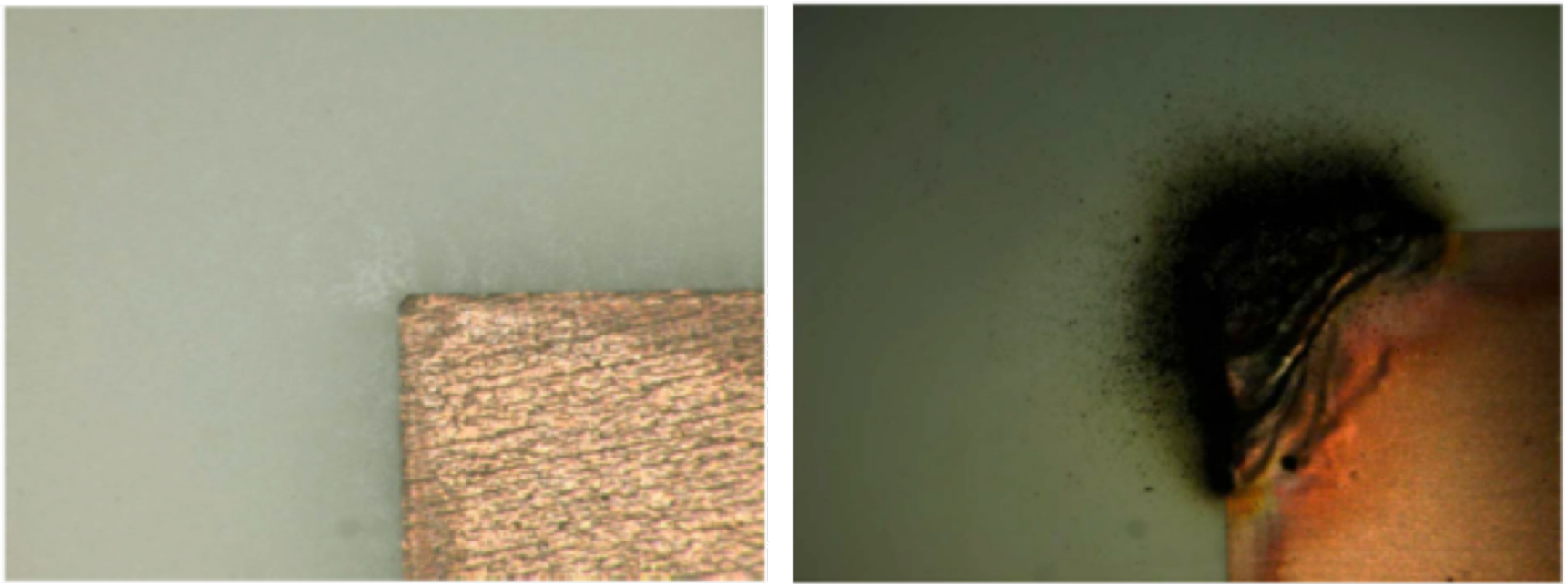
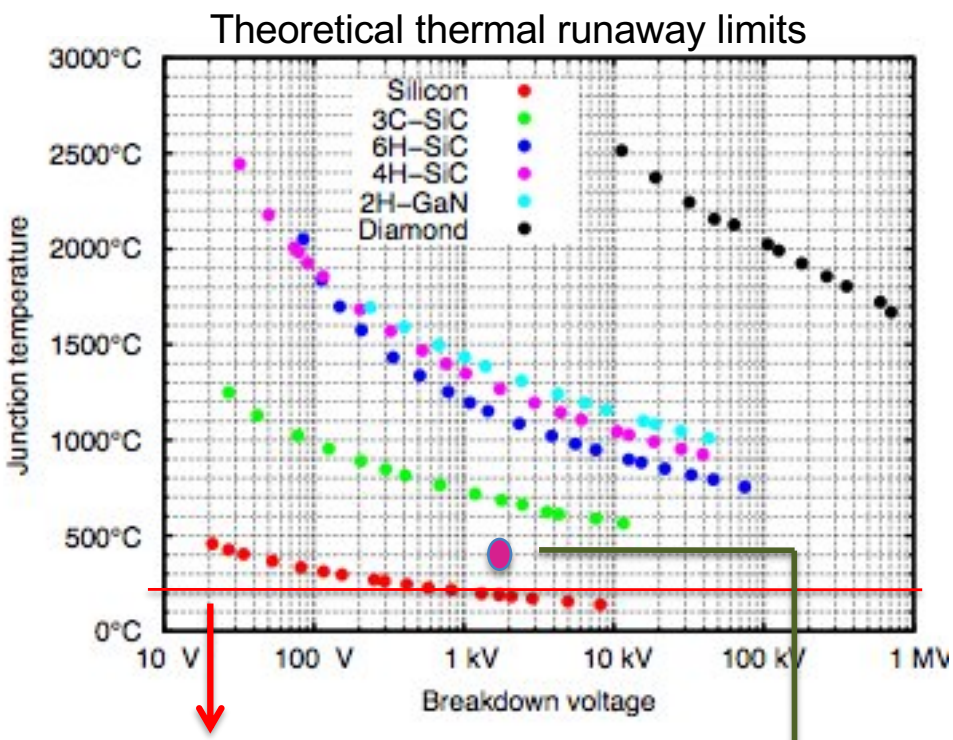


Li, Zhe et al. *Dielectrics and Electrical Insulation, IEEE Transactions on*, 18(3), pp 675, 2011

7. Challenges for the future

High temperature ability of wide band gap devices



Si limit is less than 200 ° C

Operation demonstration of 4H-SiC dies up to 400 °C.

N.B.: Tj_{max} of commercial packaged devices is still limited today at 175 ° C.

Specific characteristics induced by wide band gap semiconductor devices under operation

- **> High electric field**
  (2 to 10 MV/cm peaks)
- **> High temperature** (if needed)
  (up to 400 ° C)
- **> High voltage** (if needed)
  (up to 10 kV)
- **> Ultra fast switching**
- **> Smaller dies**

=> the WBG semiconductor die environnement has to be adapted …

CONFIDENTIAL

7. Challenges for the future

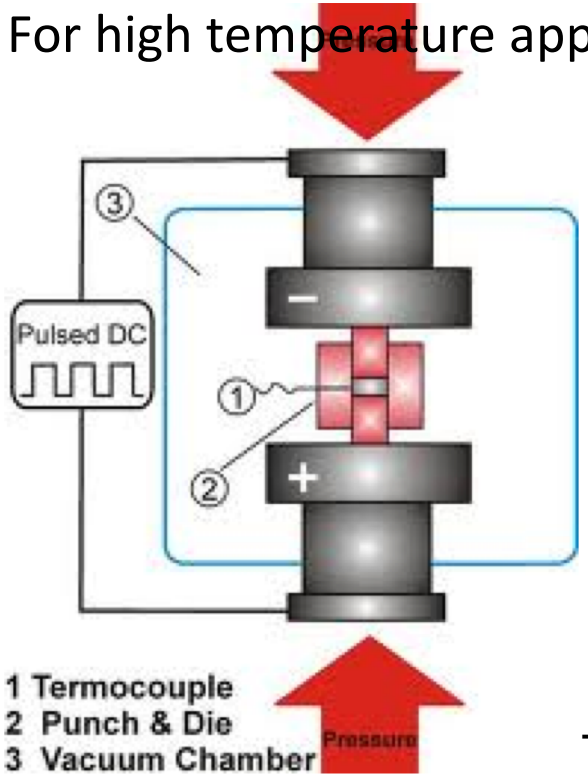
Increase in :

- Power densities and integration
- Operating voltages and dV/dt
- Operating temperatures

Will ceramics continue to be an answer ?

7. Proposals for new substrate technologies

For high temperature applications…



- *P ≤ 200 MPa max*
- *25 <T< 2000°C*

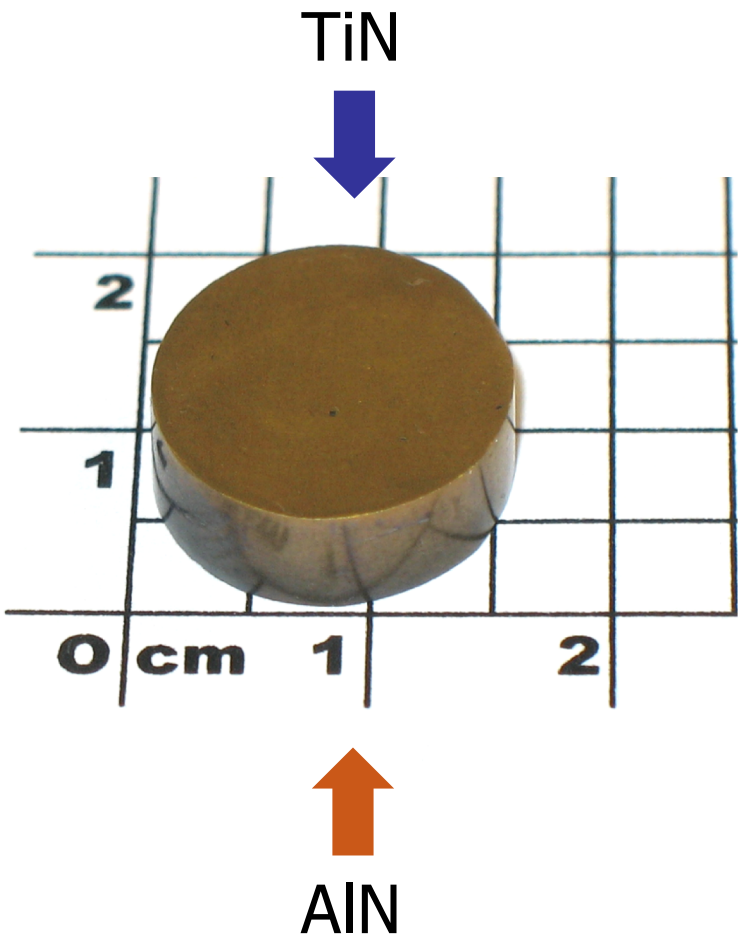
Why TiN ?

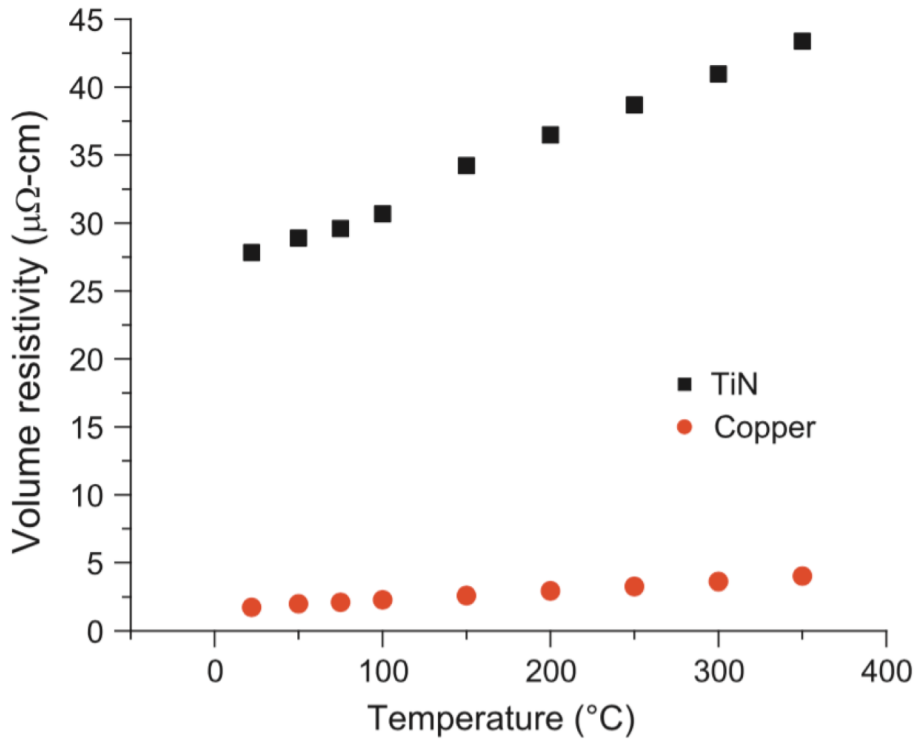
hard ceramic , good conductor, compatible CTE

	AlN	Cu	TiN
Thermal conductivity ($W.K^{-1}.m^{-1}$)	180	400	40
Electrical resistivity (μΩ.cm)	10^{20}	2	20
Coef Thermal Expansion (CTE) 20-100 °C (10^{-6} K^{-1})	4	17	9

7. Proposals for new substrate technologies

For high temperature applications…



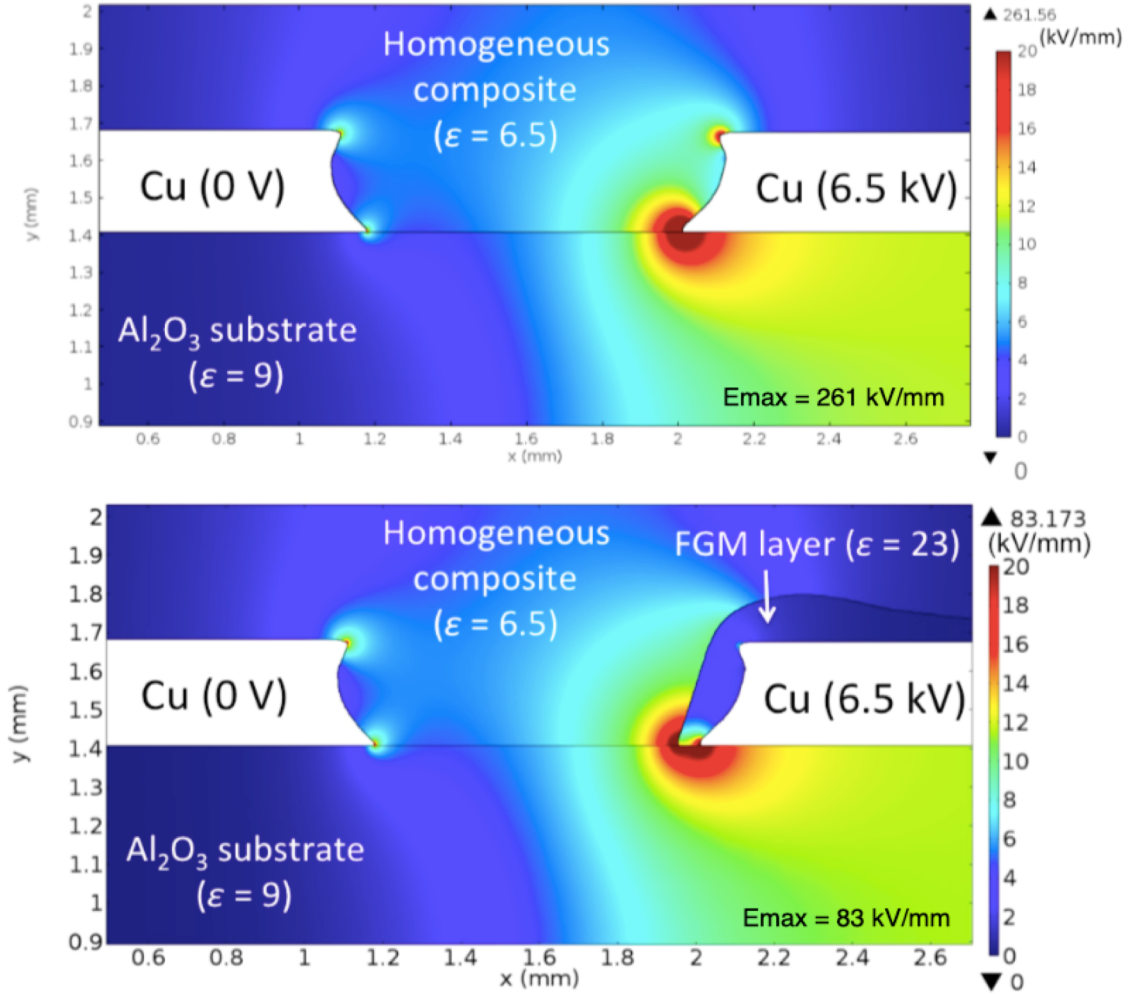


Valdez-Nava et al., Ceramics International, 2013, 8743-8749.

7. Proposals for new substrate technologies

For high voltage applications…

Triple point problem

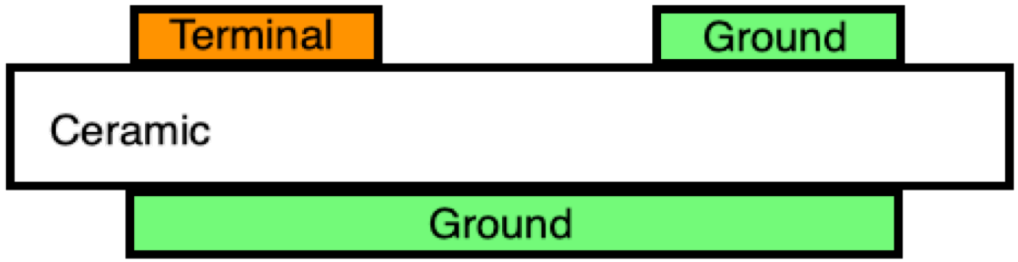


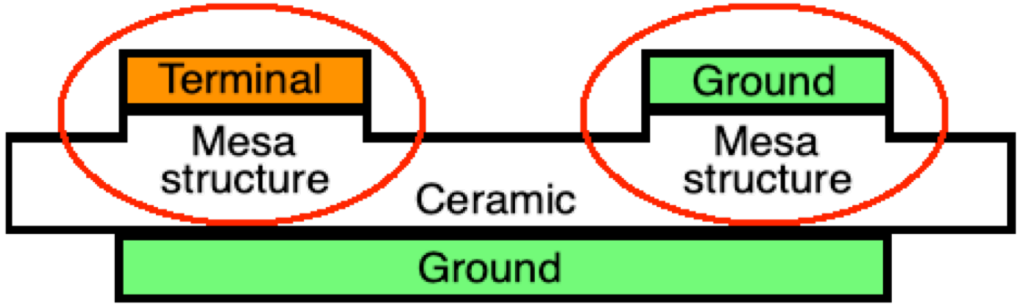
Diaham S., Valdez, Z., et al. *2018 IEEE ICD*. IEEE, 2018.

7. Proposals for new substrate technologies

For high voltage applications…

Classic structure

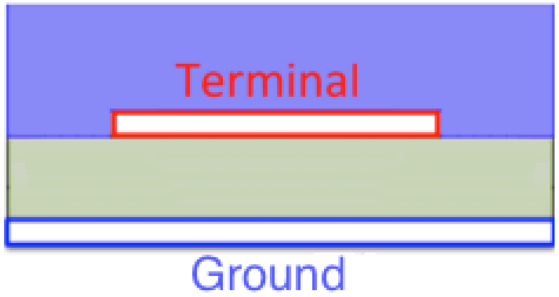


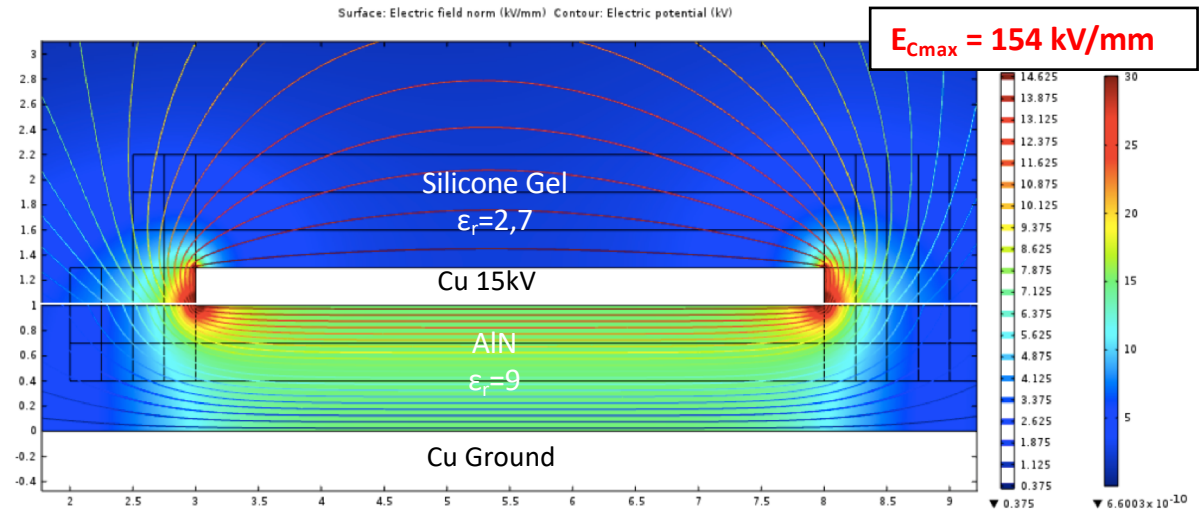


Mesa structure

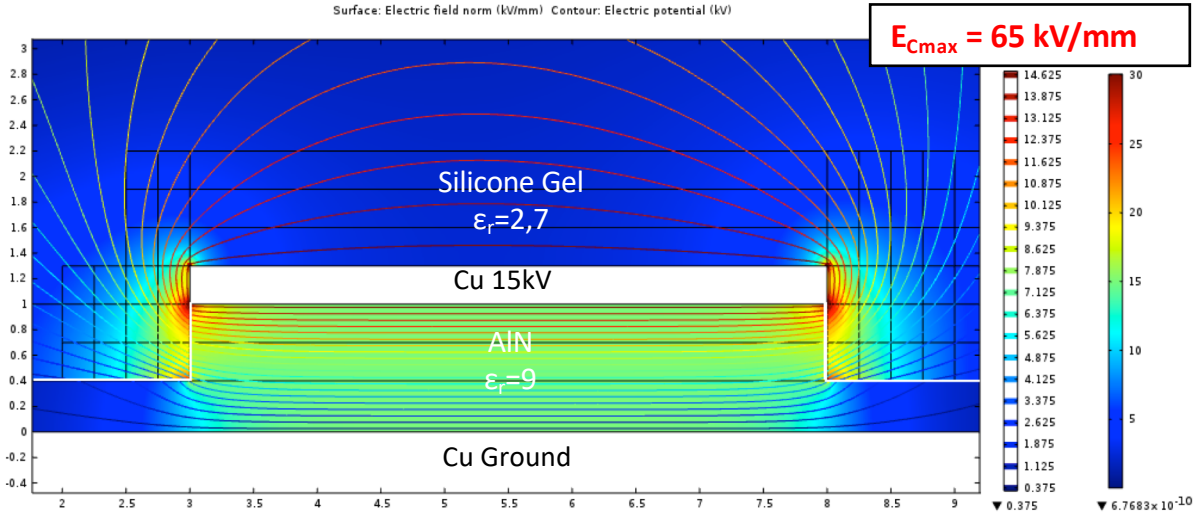
7. Proposals for new substrate technologies

Classic structure
AlN thickness: 1 mm
Voltage: 15 kV





Mesa stucture
AlN thickness : 1 mm
Voltage: 15 kV

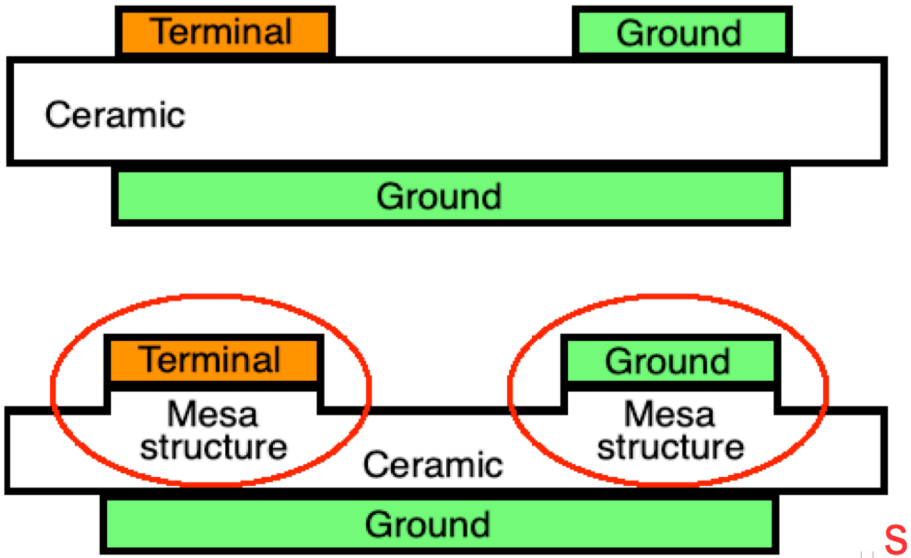


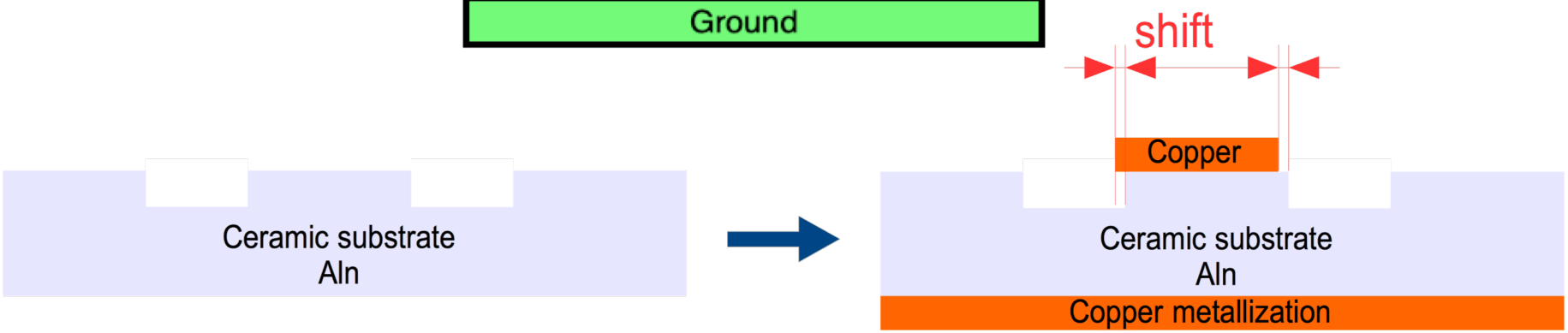
➔ Reduction of 57% in the maximum electric field

Hourdequin et al. *ICD 2016,* IEEE, 999-1002

7. Proposals for new substrate technologies

For high voltage applications…

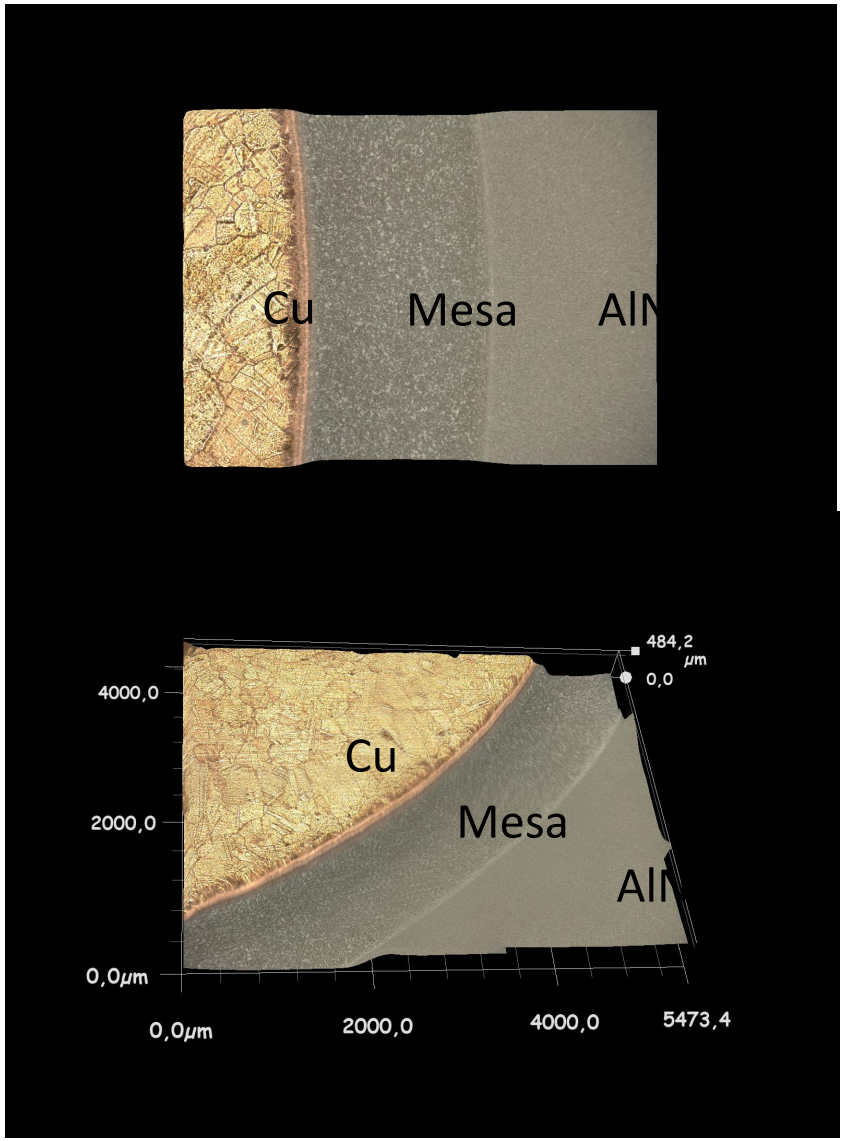


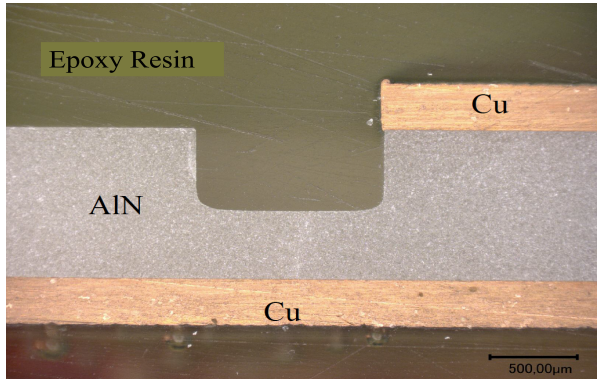


Machined substrate

Metallized substrate

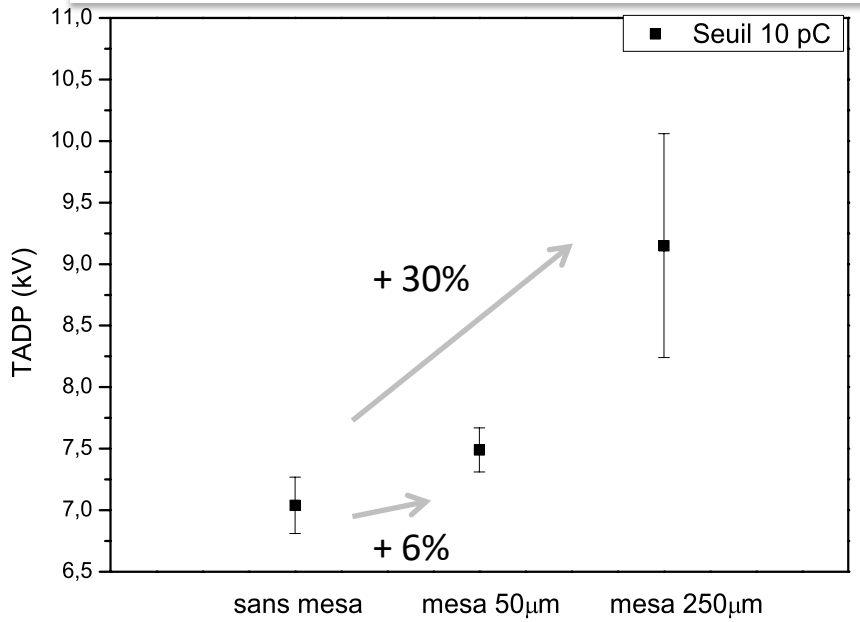
7. Proposals for new substrate technologies





Cross section

PD measurements (PDIV) @ 50Hz

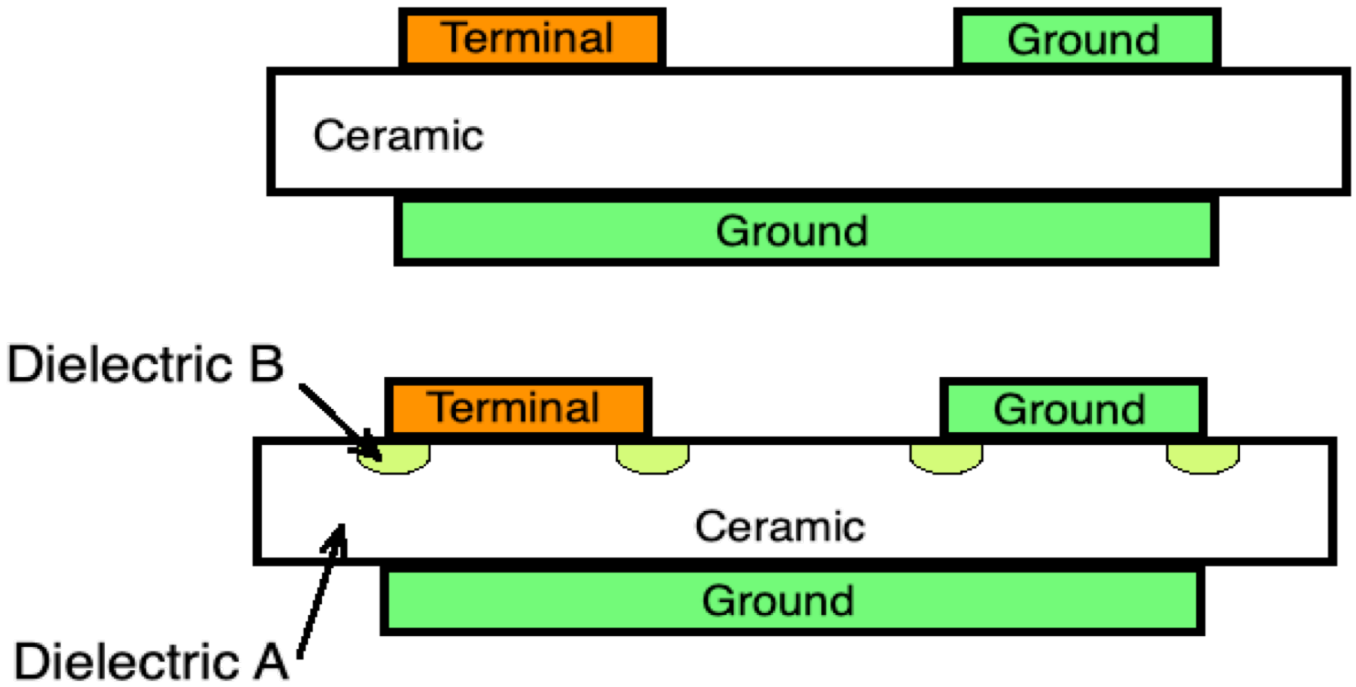


Hourdequin, PhD Thesis, Université de Toulouse, 2018.

7. Proposals for new substrate technologies

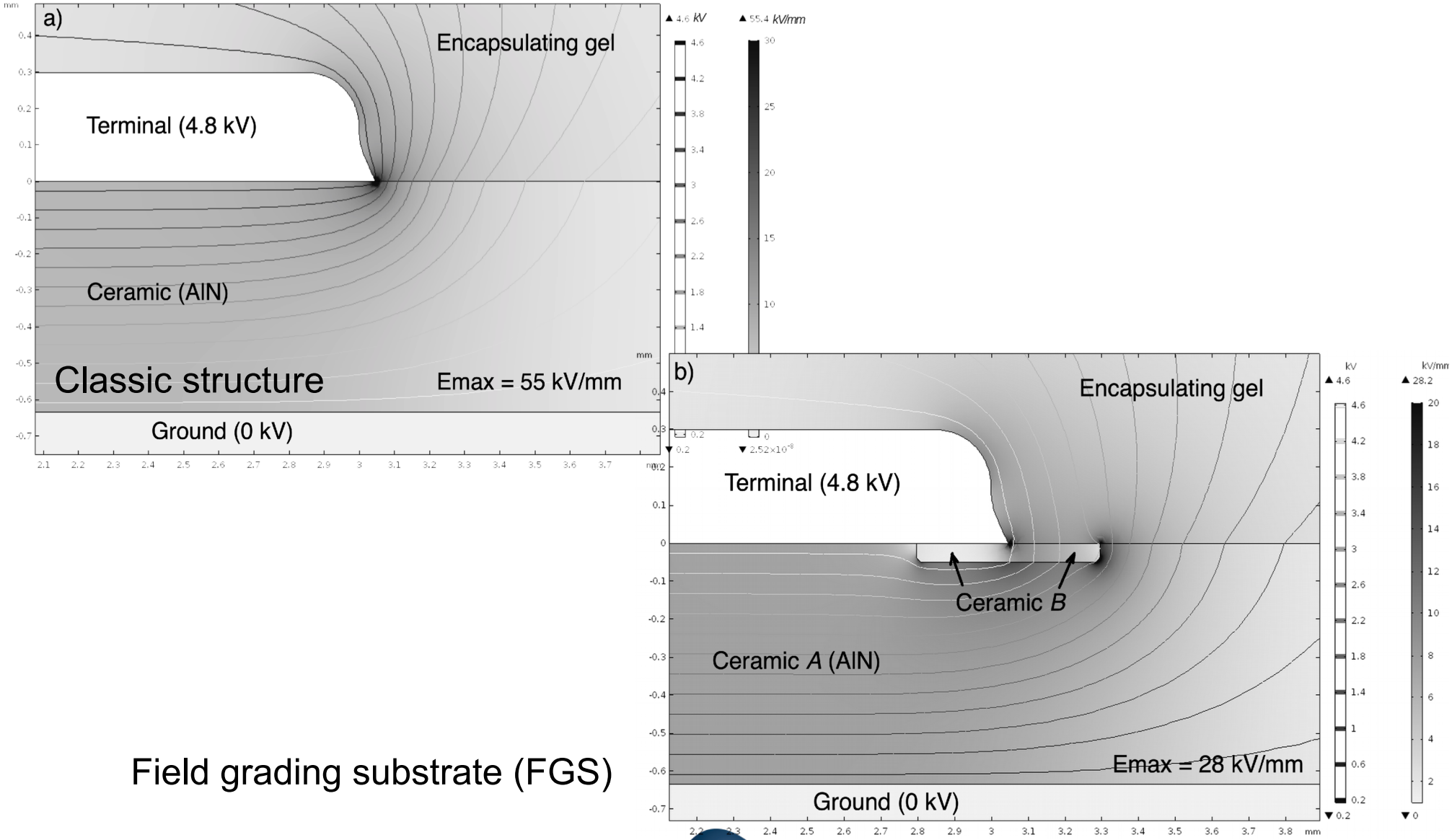
For high voltage applications…

Classic structure



Field grading substrate (FGS)

7. Proposals for new substrate technologies

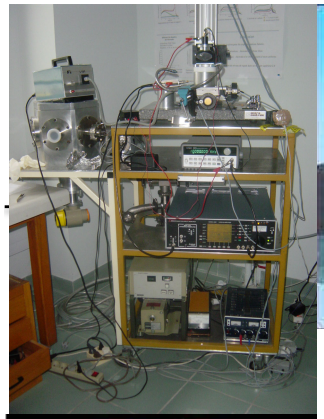


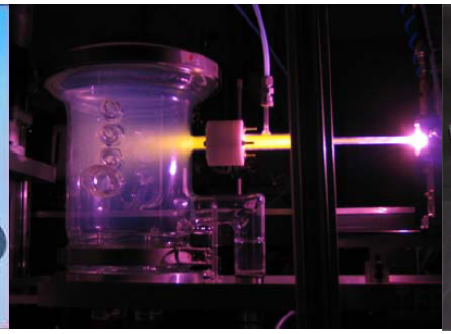
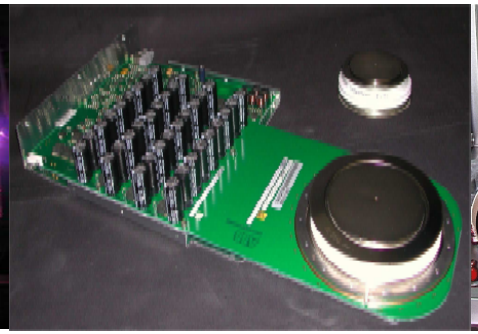
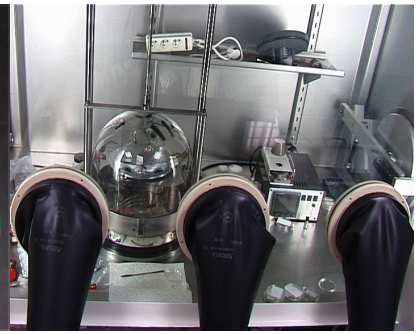
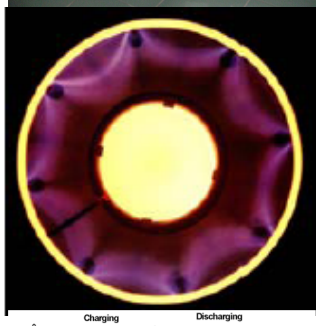
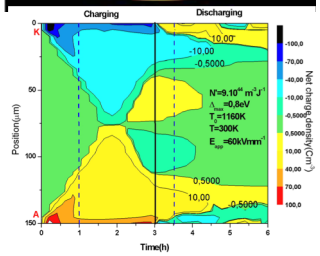
Field grading substrate (FGS)

9. Final remarks

- When high voltage insulation and heat dissipation are required, ceramic substrates remain a first choice in current applications.

- In future applications, a global approach will be required to manage the increase in voltage, electric fields and temperature.



Thanks to our founders:

AGENCE NATIONALE DE LA RECHERCHE
ANR

French National Agency for Research

DGA

Directorate General of Armaments

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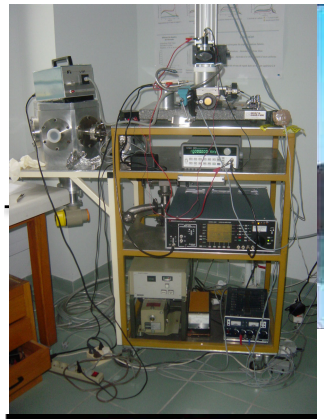

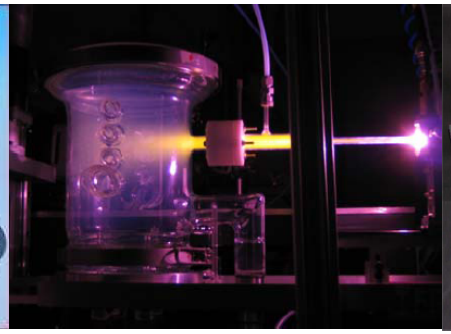
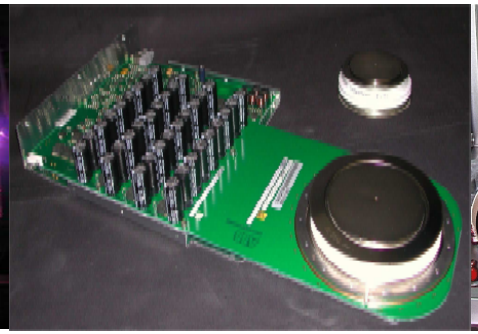
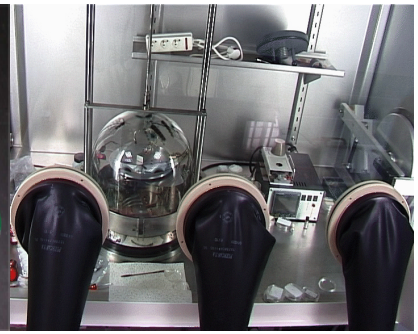
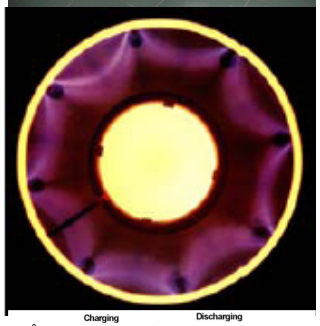
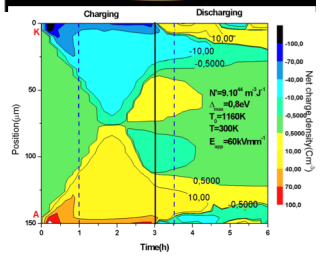

Thank you…

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