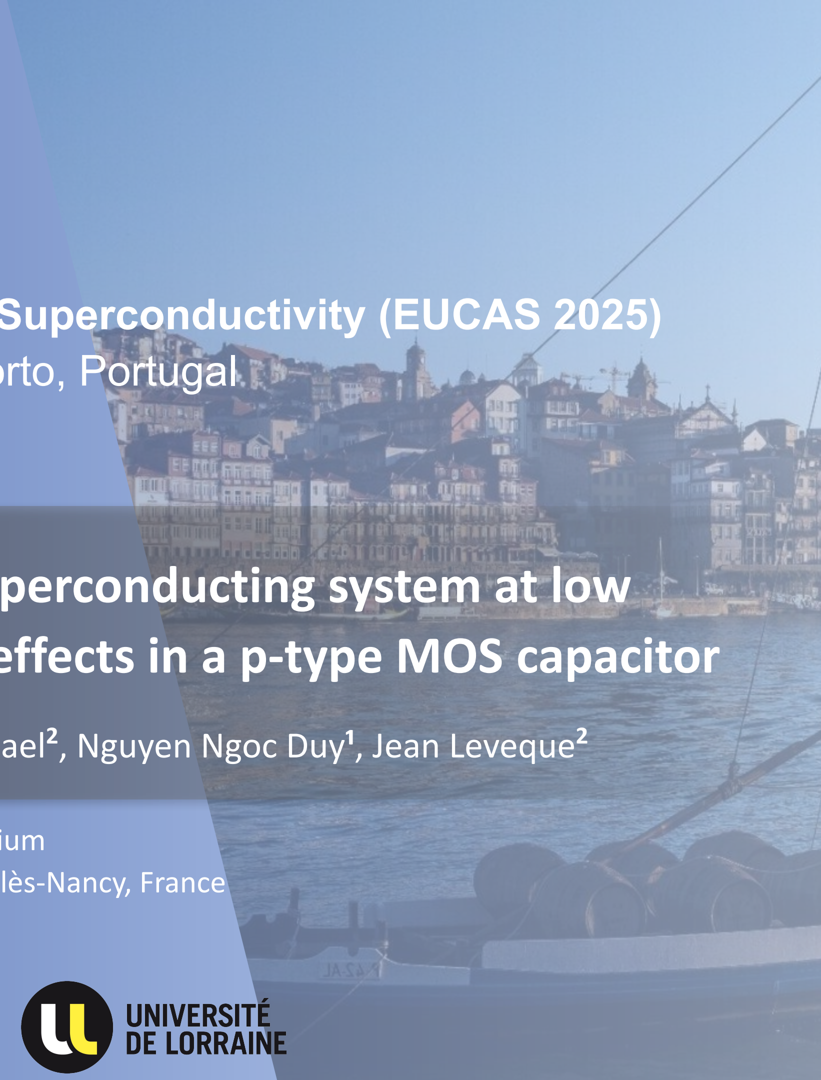

17th edition European Conference on Applied Superconductivity (EUCAS 2025)
21-25 September, 2025, Porto, Portugal

Operating the power electronics of a superconducting system at low temperatures: mitigation of interface trap effects in a p-type MOS capacitor

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UNIVERSITÉ DE LORRAINE

Introduction: electronics for power applications in cryogenic environments

➤ Growing interest in superconducting systems

- Electrical machines
- Aerospace sector
- Fusion
- High-field magnets

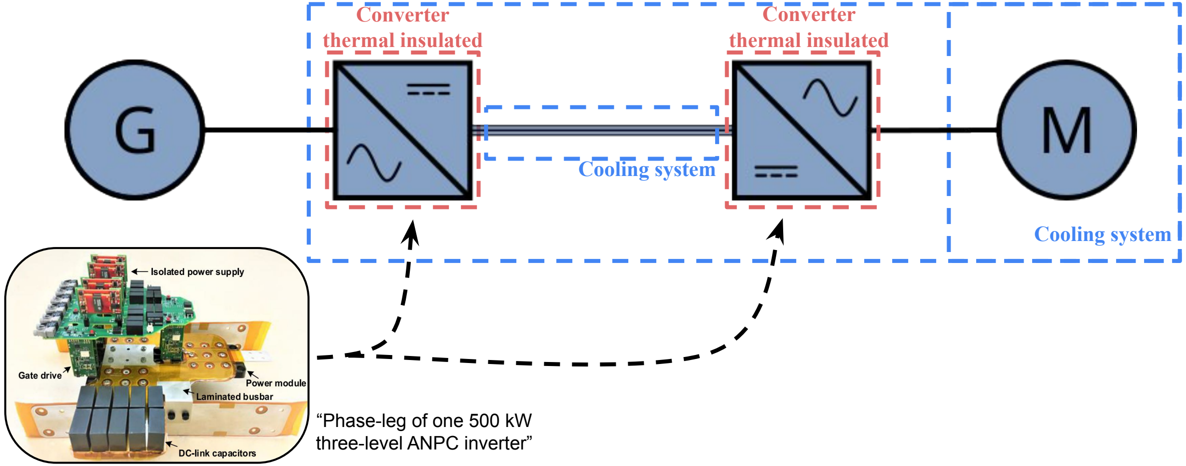
➤ Need for electronic control

➤ Can we cool down the control electronics to gain in efficiency?

- Can contribute to lower power dissipation
- Smaller volume and weight

➤ Challenge for application

- Important to understand the physical properties of power devices



[R. Chen, F. Wang. in *IEEE Open Journal of Power Electronics*, vol. 2, pp. 315-326, 2021.]

“Phase-leg of one 500 kW three-level ANPC inverter”

250 kW Partially Superconducting Flux Modulation Machine

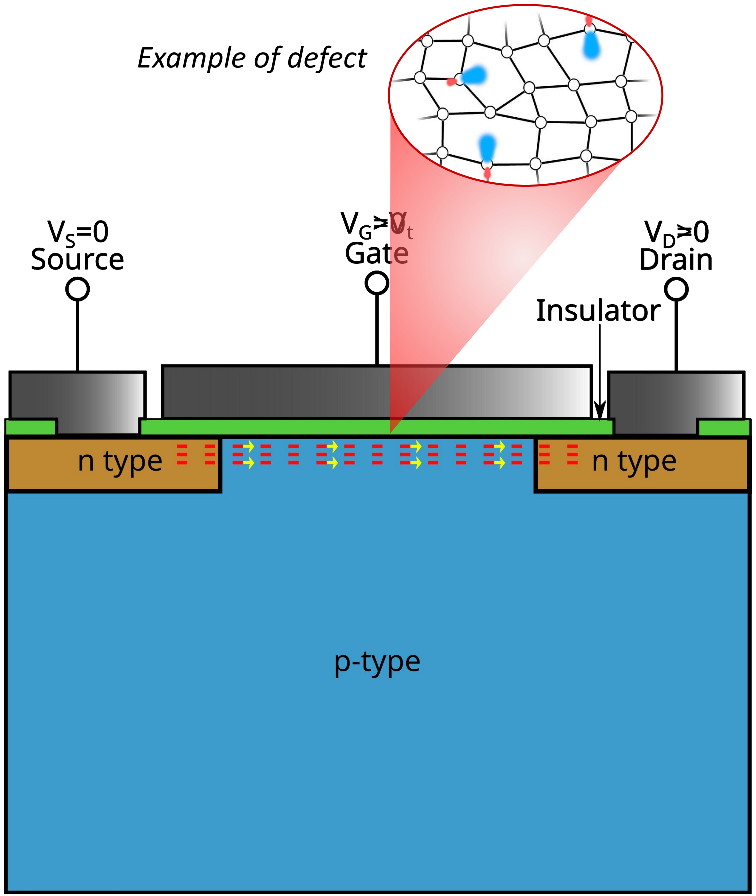
[Dorget, R., *et al*. in *IEEE Transactions on Applied Superconductivity*, vol. 35, no. 5, 2025.]

Fundamental concepts of MOSFET

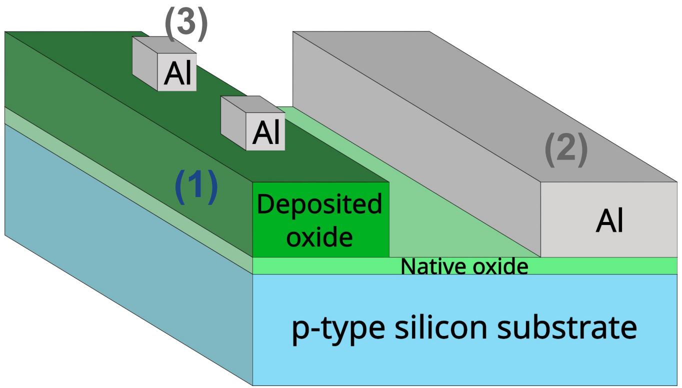
- $V_G = 0$
  Low conductivity between Source and Drain

- $V_G > V_t$
  Formation of conductive channel between Source and Drain
  - Related to the electrostatics of the MOS stack
  - Impacted by defects in the MOS stack

p type = holes as majority charge carriers
n type = electrons as majority charge carriers

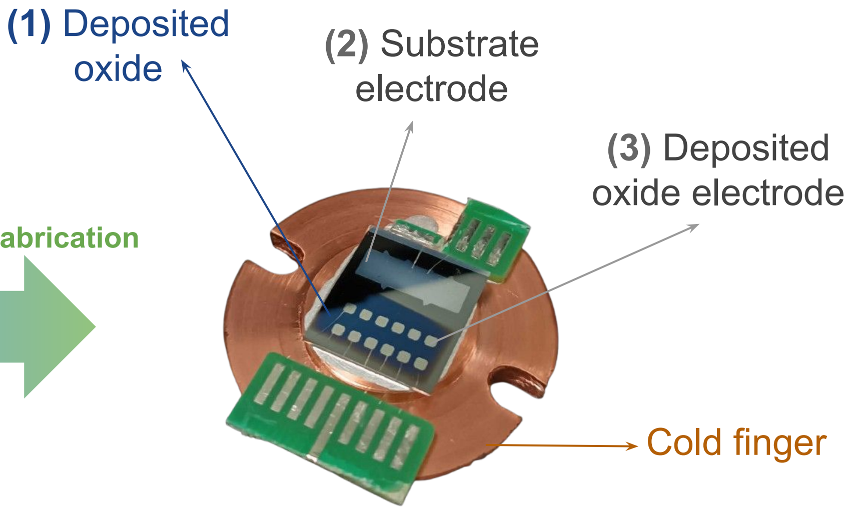


Fabricated MOS capacitor for experimental studies



Design

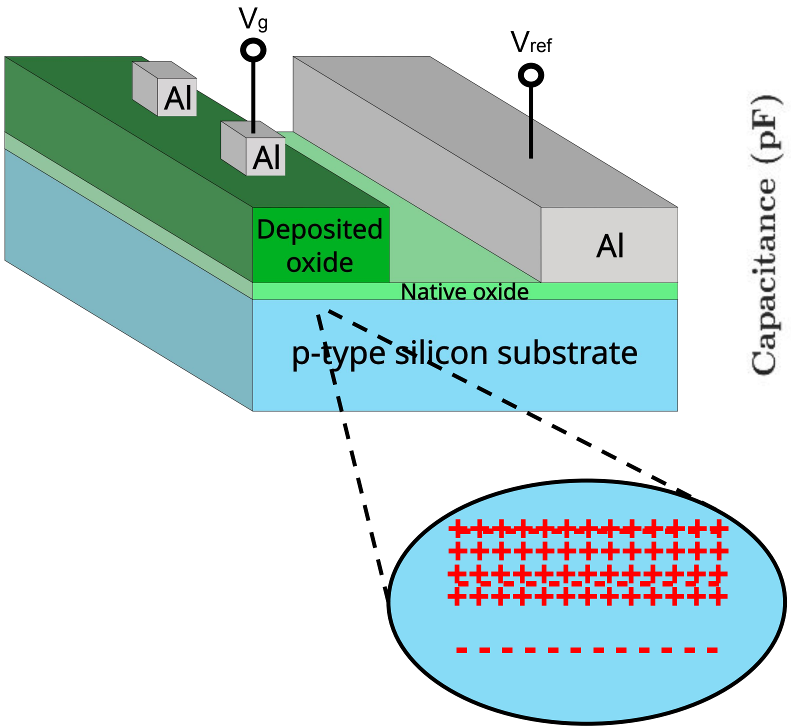
Fabrication

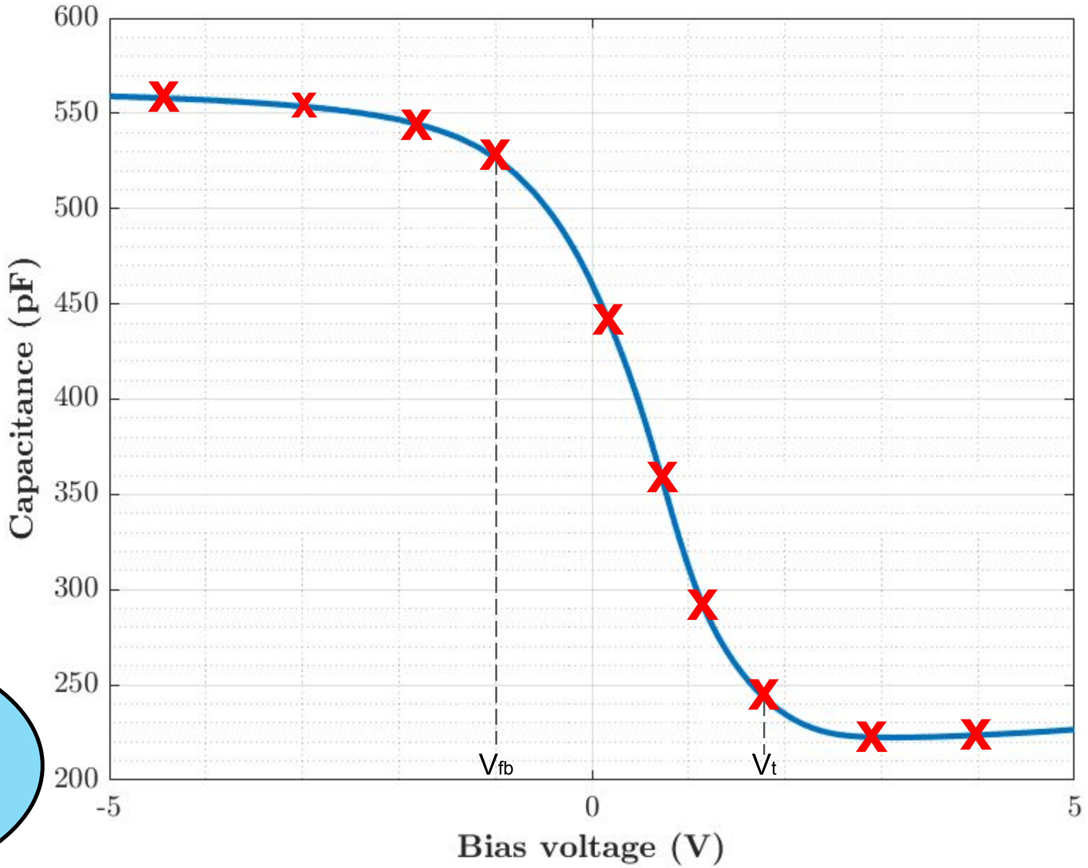


RF sputtered SiO_2 MOS capacitor structure designed on purpose with physical characteristics:

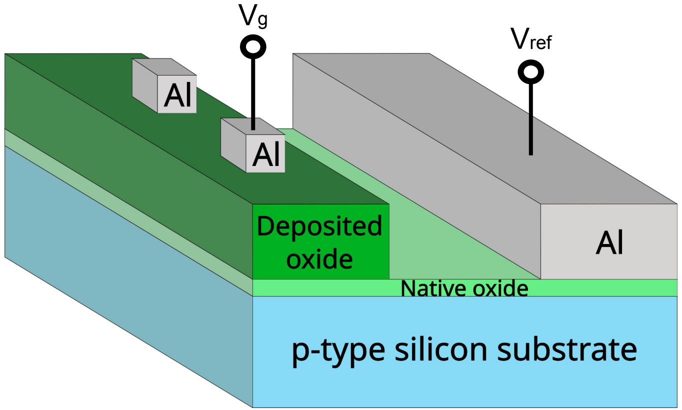
- Thickness (100 nm)
- Roughness (RMS = 0,2 nm)
- Stoichiometry (SiO_x)

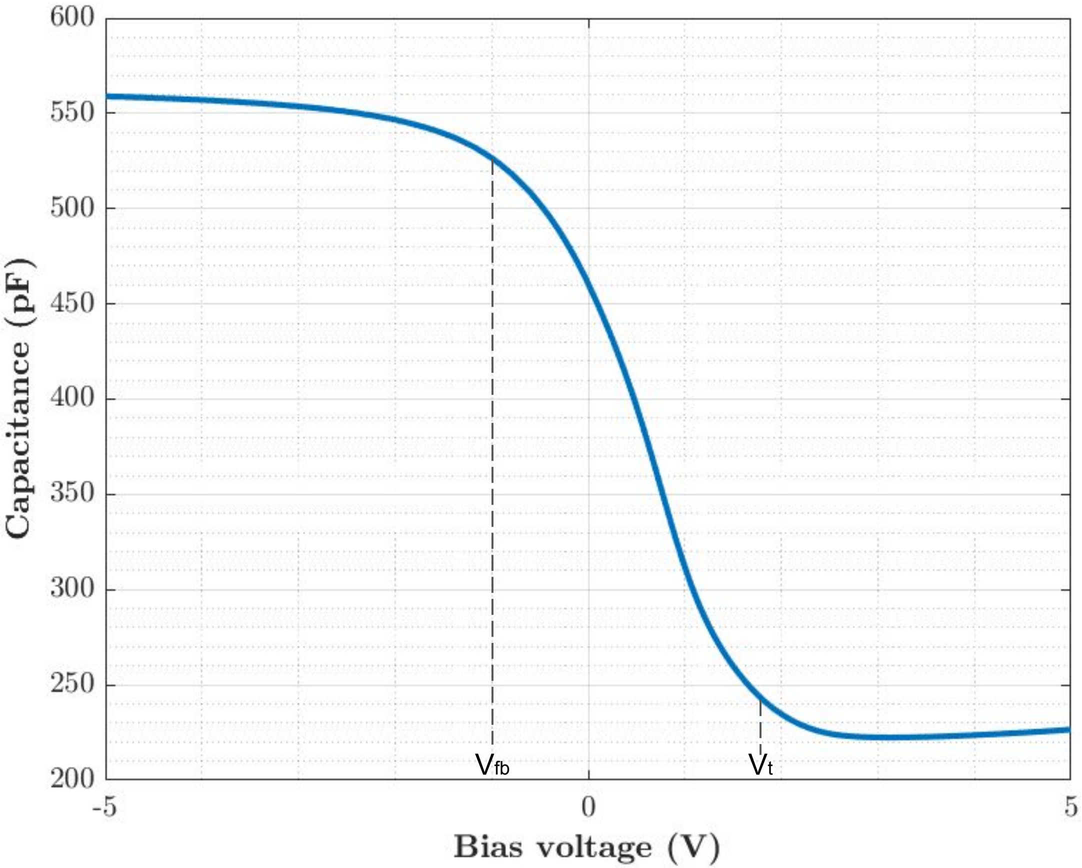
Characteristic C-V curves





- Characteristic C-V curves

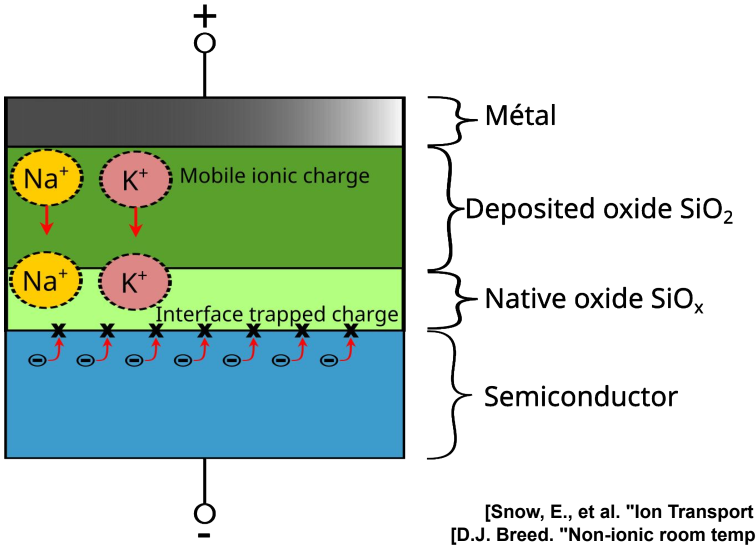


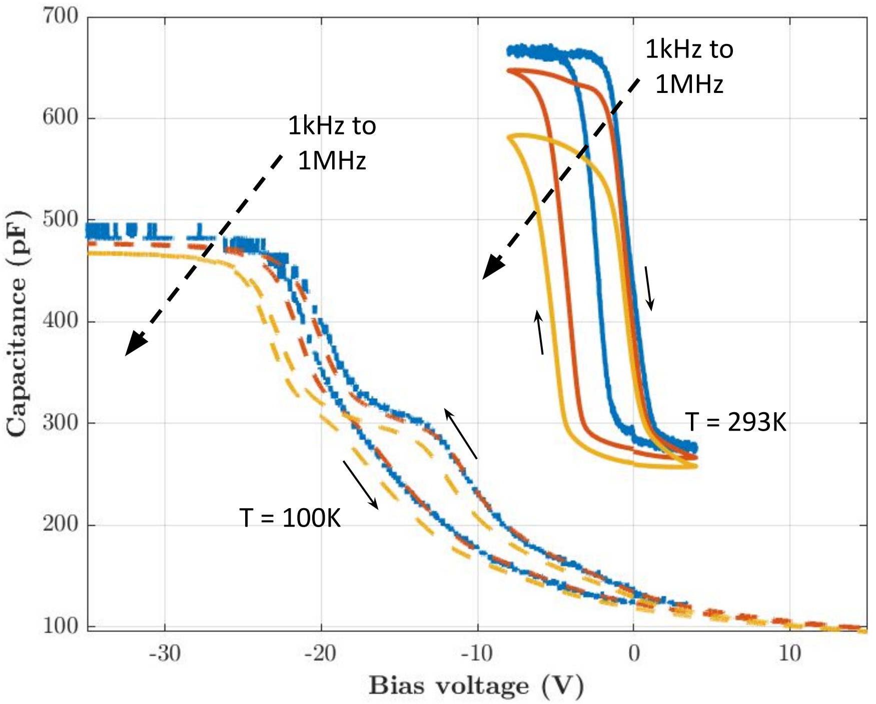


Results: C-V characteristics at room temperature and at 100K

Trap-induced effects

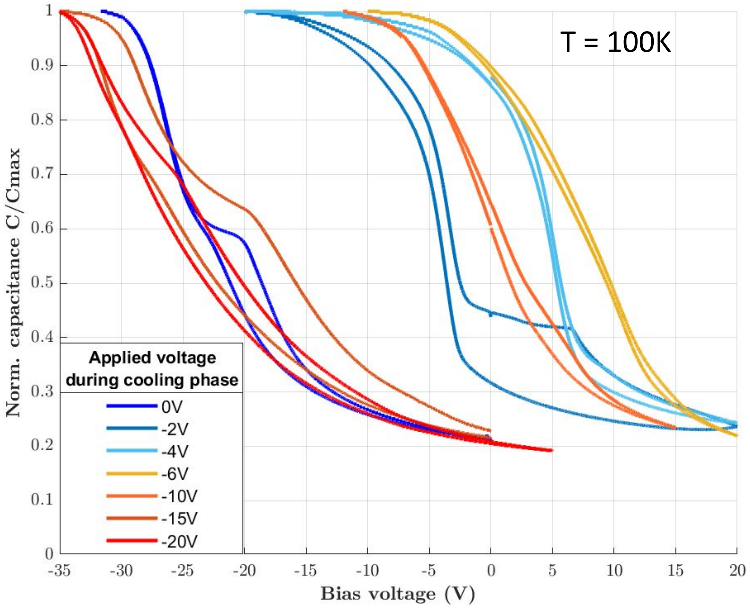
- Hysteresis in Voltage Sweep
- C(f) dispersion
- Cryogenic behavior
  - C-V stretch-out effect
  - Bump effect

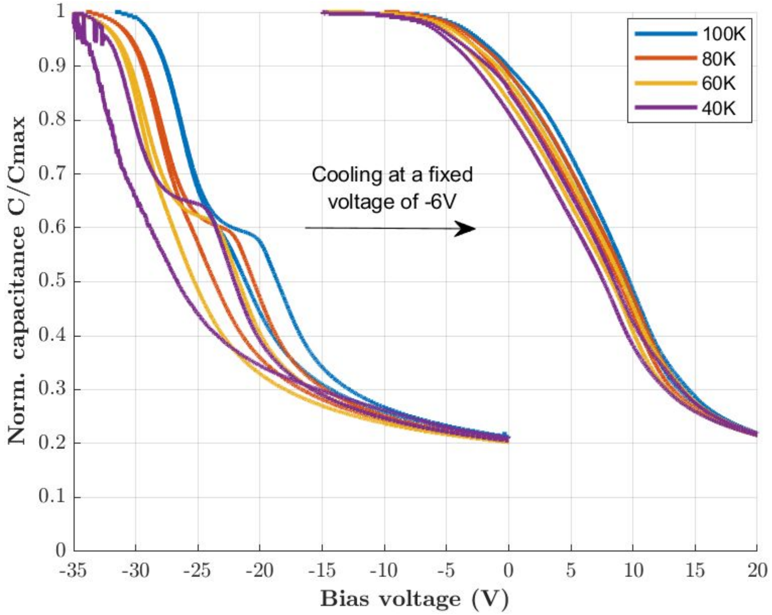


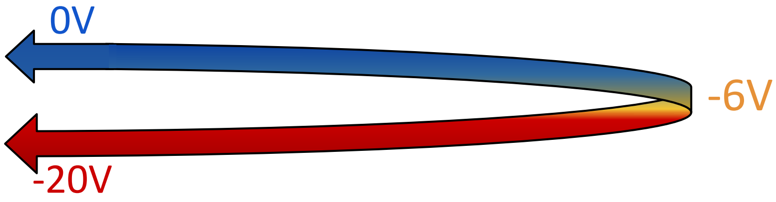


[Snow, E., et al. "Ion Transport Phenomena in Insulating Films," in Journal of Applied Physics, vol. 36, no. 5, pp. 1664-1673, 1965.]
[D.J. Breed. "Non-ionic room temperature instabilities in MOS devices," in *Solid-State Electronics*, vol. 17, no. 12, pp. 1229-1243, 1974.]

Results: impact of bias voltage while cooling the sample





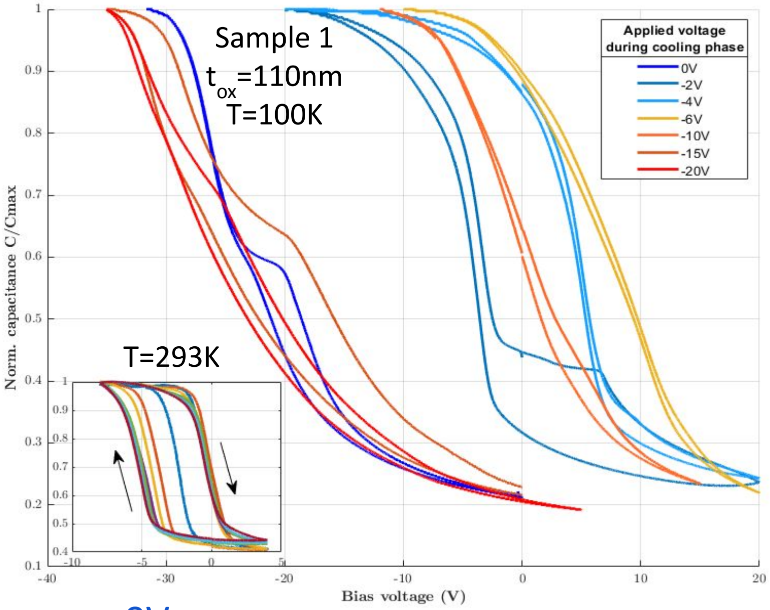


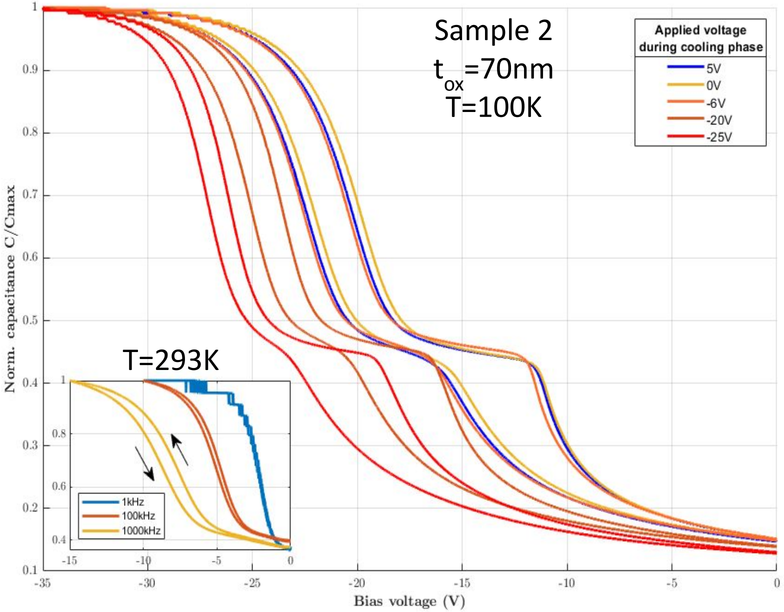
0V

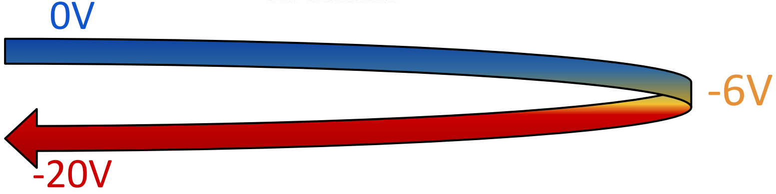
-6V

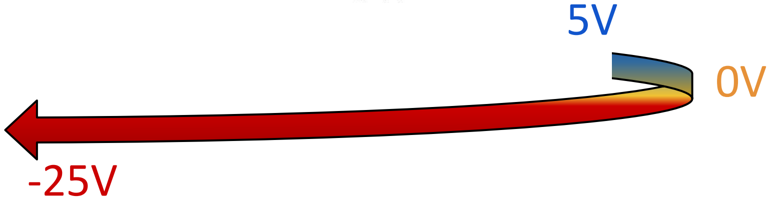
-20V

Results: cryogenic behavior under the influence of low mobile ionic charge

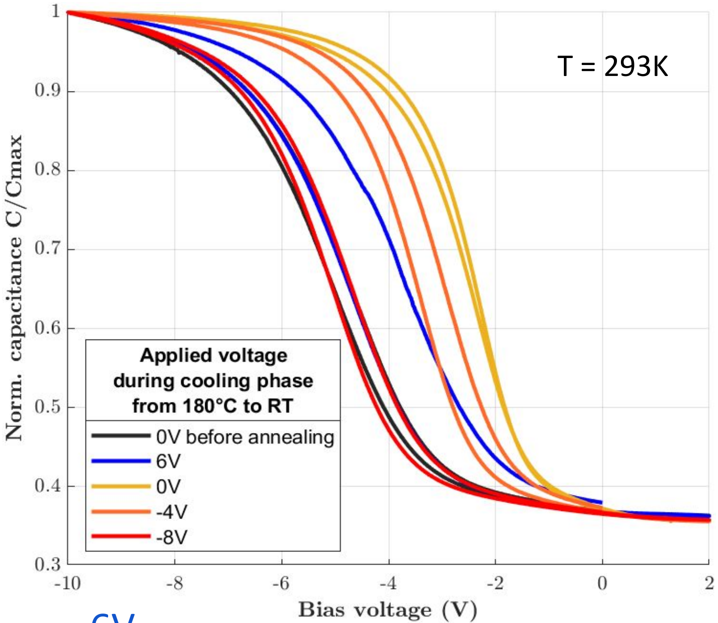


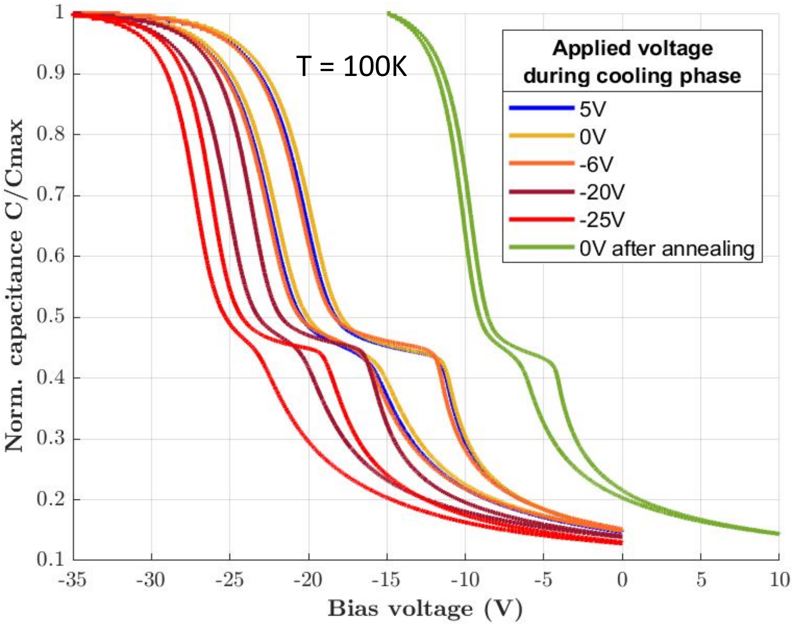


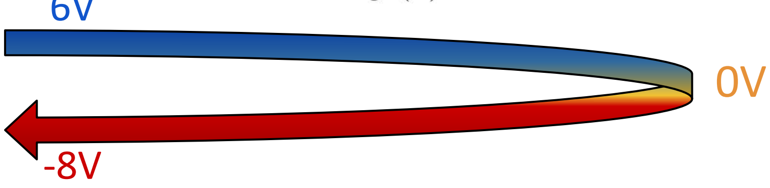




Results: Sample 2, annealing treatment







Conclusion

To keep in mind

- Defects in MOS capacitors can greatly affect device performance, especially at low temperatures!
- Applying a voltage bias to the MOS during the cooling phase can help improve the device response

Perspectives

- Annealing MOS devices before cooling
- Extended physical-chemical characterisation of the MOS stack

Thank you for your attention!

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UNIVERSITÉ DE LORRAINE

Lifetime Electron Emission to conduction band

$$R_{en} = e_n N_t f_F(E_t) \qquad (1)$$

$$R_{cn} = C_n N_t\big(1 - f_F(E_t)\big)n \qquad (2)$$

R_{en} *- Emission rate (#/cm3-s)*

R_{cn} *- Capture rate (#/cm3-s)*

C_n *- Constant proportional to electron-capture cross section*

N_t *- Total concentration of trapping centers*

n *- Electron concentration **in the conduction band***

$f_F(E_t)$ *- Fermi function at the trap energy*

e_n *- Constant or **Emission Coefficient:** The probability per unit time that a trapped electron is thermally emitted*

Thermal equilibrium:

$$R_{en} = R_{cn} \qquad (3)$$

Using Boltzmann approximation $E_t - E_F \gg kT$ and consequently $f_F(E) \simeq \exp\left(\frac{-(E-E_F)}{kT}\right)$:

$$e_n = n_0 C_n \qquad (4)$$

E_F *- Fermi level*

n_0 *- Electron concentration **in the conduction band** at thermal equilibrium*

Where :

$$n_0 = N_c \exp\left(\frac{-(E_c - E_F)}{kT}\right) \qquad (5)$$

Finally, emission time constant is the characteristic **time it takes for a single carrier to be emitted once it is trapped**, considering $1 - f_F(E_t) \simeq 1$ from Boltzmann approximation:

$$\tau_{e,n} = \frac{1}{e_n} = (C_n N_c)^{-1} \exp\left(\frac{(E_c - E_t)}{kT}\right) \qquad (6)$$

$$\tau_{e,n} = \frac{1}{e_n} = (\sigma_n \bar{v} N_c)^{-1} \exp\left(\frac{(E_c - E_t)}{kT}\right) \qquad (7)$$

σ_n *- Electron capture cross section*

$\bar{v}$ *- Thermal velocity*

Lifetime Hole Emission to valence band

$$R_{eh} = c_h N_t\big(1 - f_F(E_t)\big) \qquad (1)$$

$$R_{ch} = C_p N_t f_F(E_t) p \qquad (2)$$

R_{eh} *- Emission rate (#/cm3-s)*

R_{ch} *- Capture rate (#/cm3-s)*

C_p *- Constant proportional to hole-capture cross section*

N_t *- Total concentration of trapping centers*

p *- Hole concentration **in the valence band***

$f_F(E_t)$ *- Fermi function at the trap energy*

c_h *- Constant or **Emission Coefficient:** The probability per unit time that a trapped hole is thermally emitted*

Thermal equilibrium:

$$R_{eh} = R_{ch} \qquad (3)$$

Using Boltzmann approximation $E_t - E_F \gg kT$ and consequently $f_F(E) \simeq \exp\left(\frac{-(E-E_F)}{kT}\right)$:

$$c_h = p_0 C_p \qquad (4)$$

E_F *- Fermi level*

p_0 *- Hole concentration **in the valence band** at thermal equilibrium*

Where :

$$p_0 = N_V \exp\left(\frac{-(E_F - E_V)}{kT}\right) \qquad (5)$$

Finally, emission time constant is the characteristic **time it takes for a single carrier to be emitted once it is trapped**, considering $1 - f_F(E_t) \simeq 1$ from Boltzmann approximation:

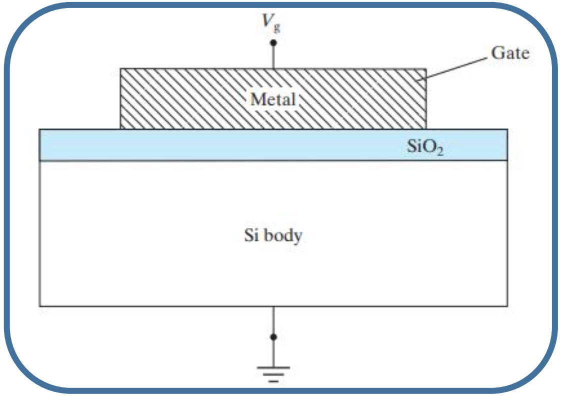
$$\tau_{e,h} = \frac{1}{c_h} = \left(C_p N_V\right)^{-1} \exp\left(\frac{(E_t - E_V)}{kT}\right) \qquad (6)$$

$$\tau_{e,h} = \frac{1}{c_h} = (\sigma_h \bar{v} N_V)^{-1} \exp\left(\frac{(E_t - E_V)}{kT}\right) \qquad (7)$$

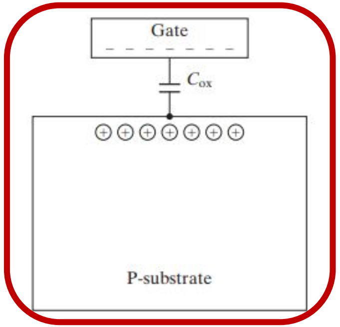
σ_h *- Electron capture cross section*

$\bar{v}$ *- Thermal velocity*

$$\tau_c = \frac{1}{\sigma v_{\mathrm{th}} N}$$

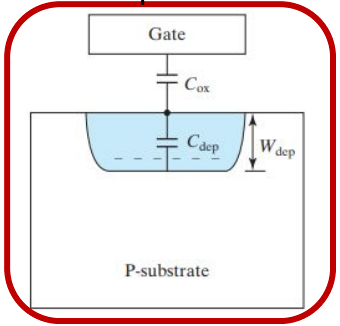


Accumulation



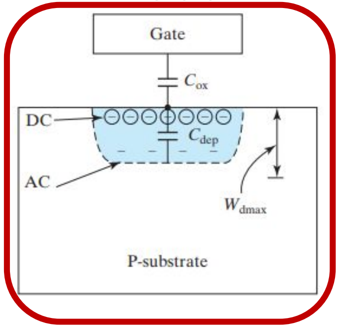
$V_g < V_{fb}$

Depletion

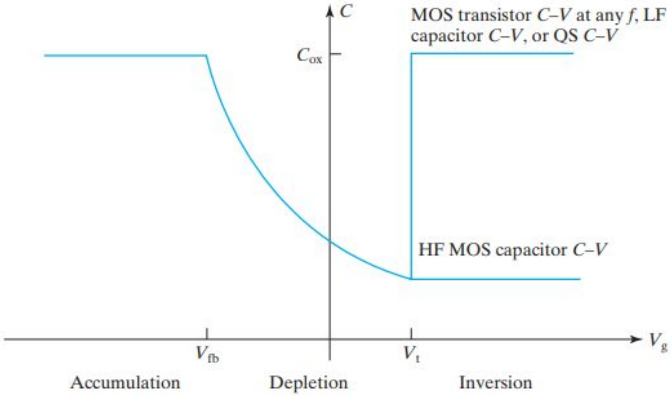


$V_g > V_{fb}$

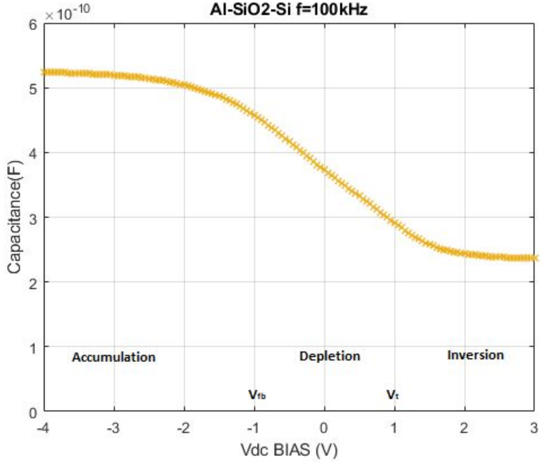
Inversion



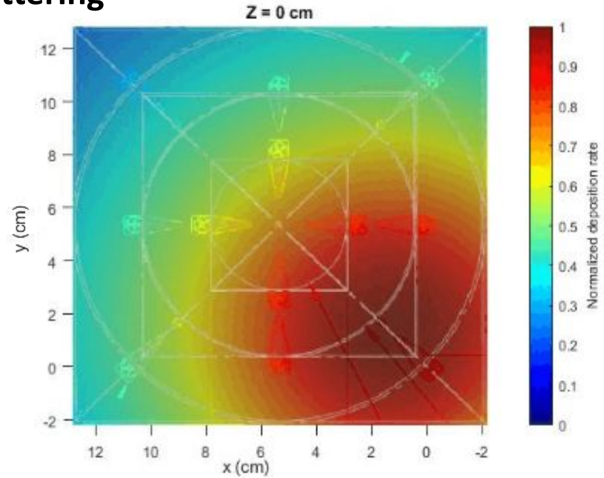
$V_g > V_t$

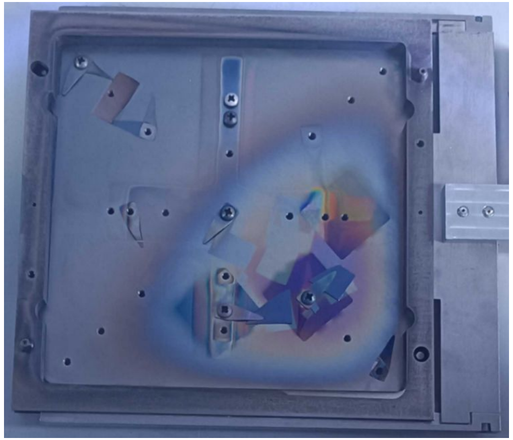


[Hu, C. (2010). *Modern semiconductor devices for integrated circuits / Chenming Calvin Hu.* Prentice Hall.]

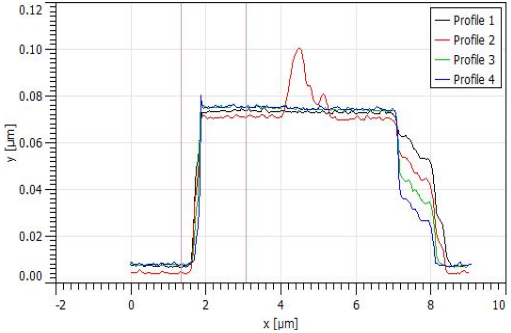


RF sputtering

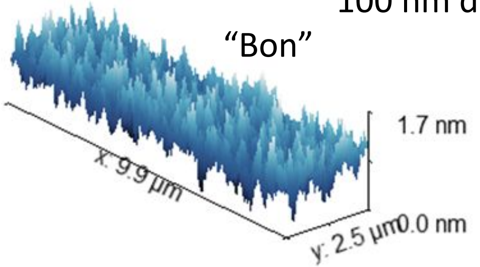




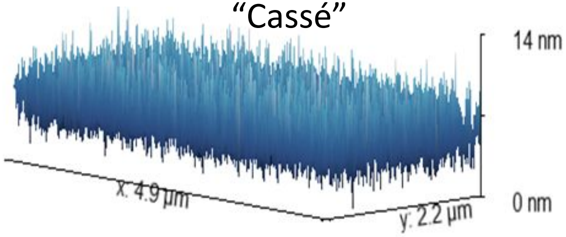
AFM (Atomic Force microscope)



100 nm de SiO_2



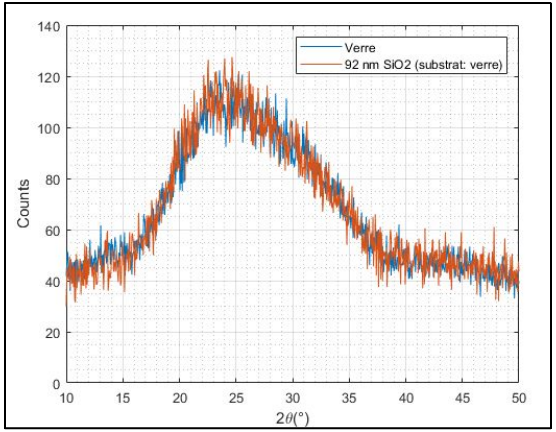
“Bon”



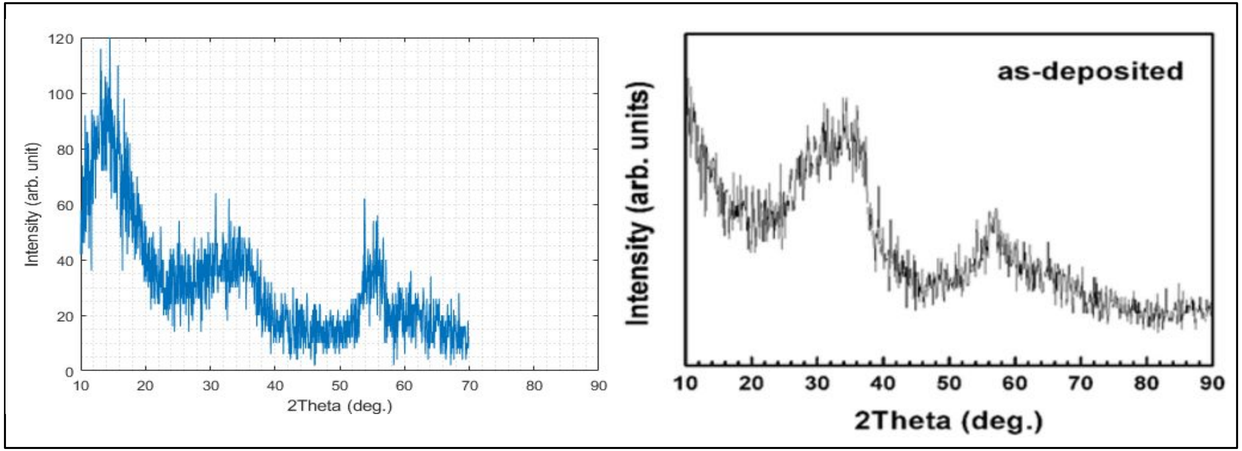
“Cassé”

GIXRD (Grazing Incidence X-Ray Diffraction)

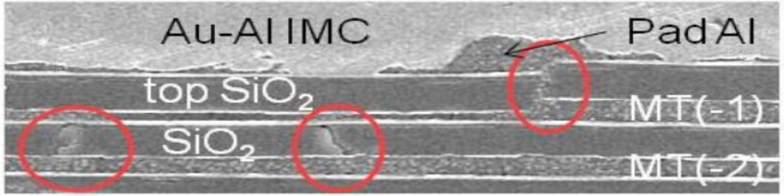
SiO_2



Ga_2O_3



Câblage (wirebonding)



[Hunter, Stevan & Rasmussen, Bryce & Ruud, Troy & Brizar, Guy & Vanderstraeten, Daniel & Martinez, Jose & Salas, Cesar & Salas, Marco & Sheffield, Steven & Schofield, Jason & Wilkins, Kyle. (2011). Use of harsh wire bonding to evaluate various bond pad structures.]