



New graphical representation of impedance data

Investigation of bulk and grain boundaries conductivities

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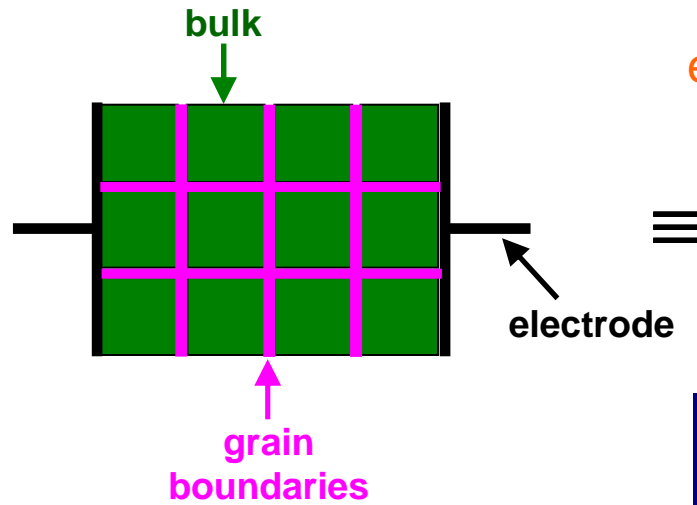
*Katarino, Bulgaria
13th-17th September 2009*



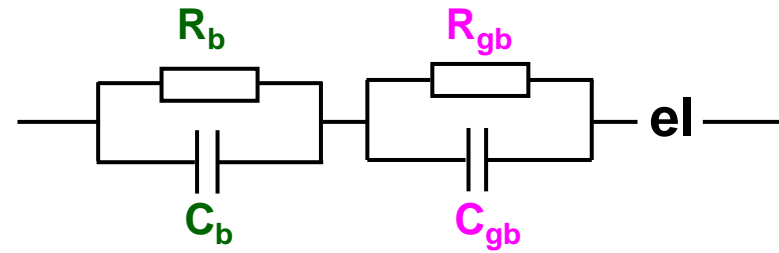
*Workshop
"Advances and Innovations in SOFCs"*



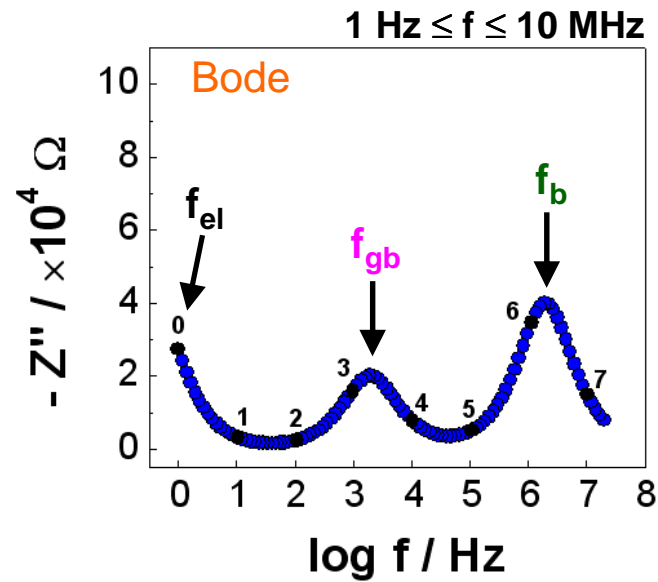
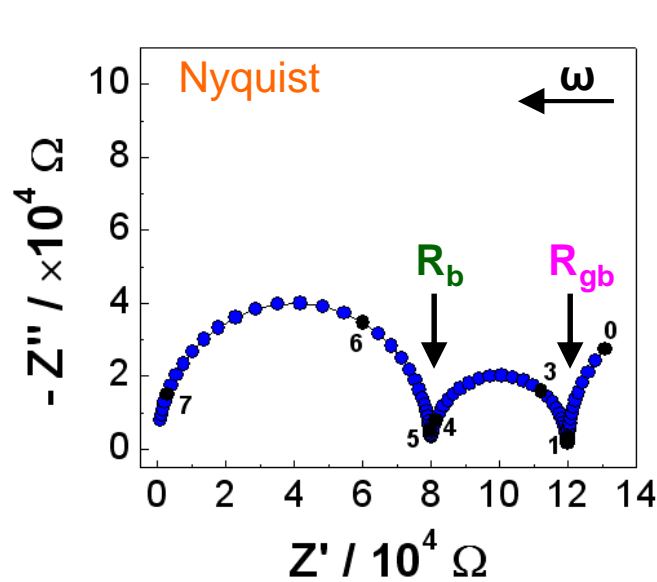
Bricklayer model



electrochemical system \equiv electrolyte material

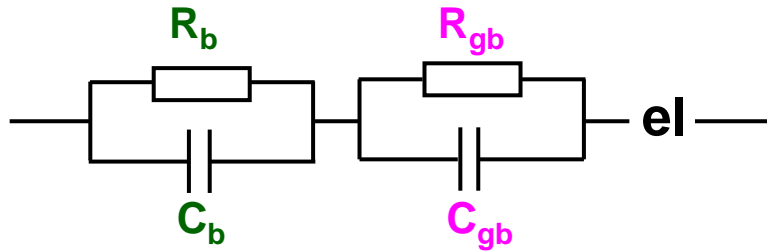


First case : $\frac{f_b}{f_{gb}} = 1000$

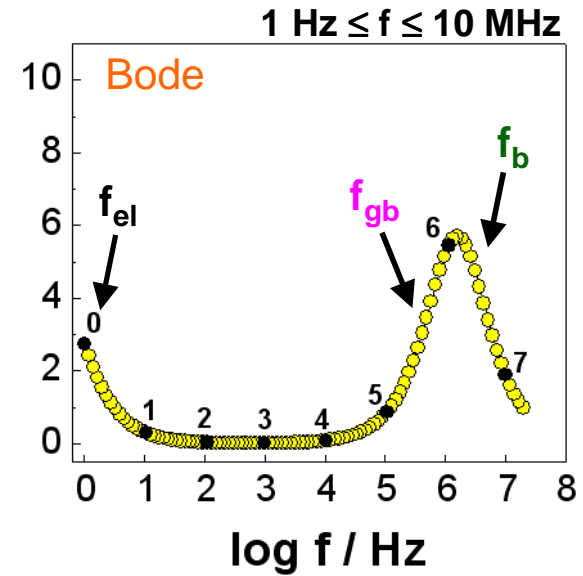


Bricklayer model

system \equiv electrolyte material

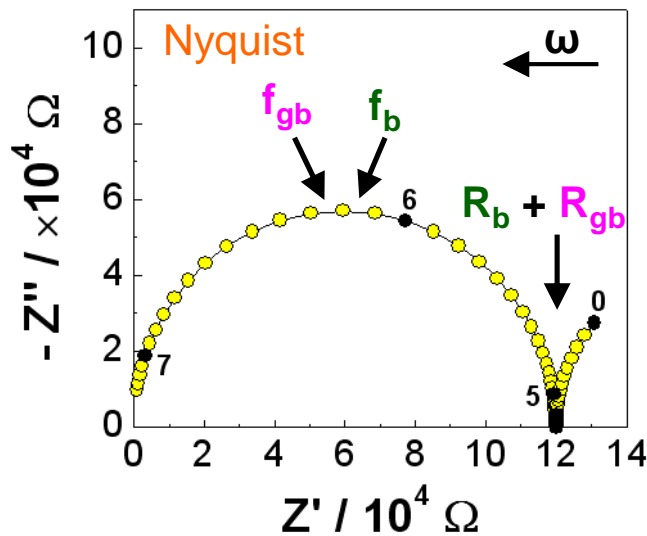


Second case : $\frac{f_b}{f_{gb}} = 2$



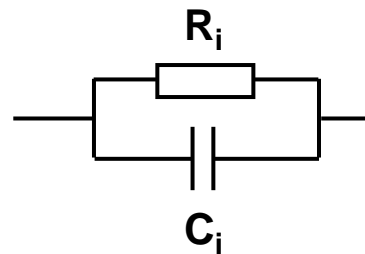
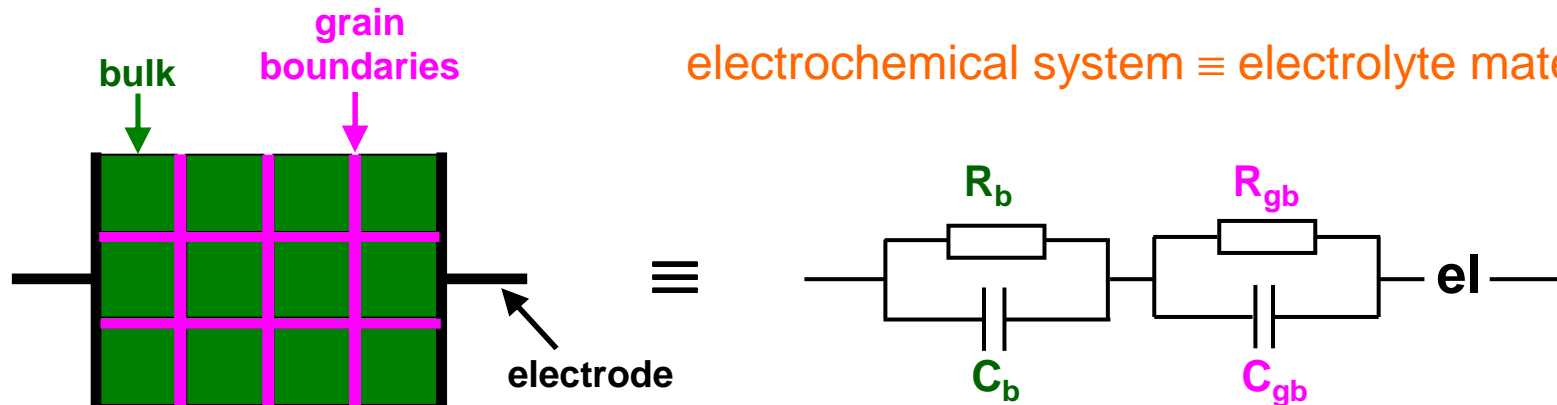
Bulk and grain boundaries processes are strongly overlapped

New complex plane



Theoretical approach

electrochemical system \equiv electrolyte material



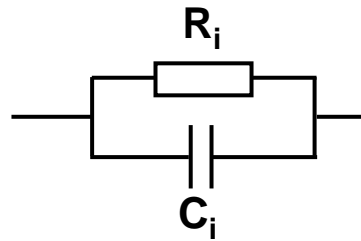
$$Z_{R/C} = \frac{R_i}{1 + R_i^2 \times C_i^2 \times \omega^2} - j \frac{R_i^2 \times C_i \times \omega_i}{1 + R_i^2 \times C_i^2 \times \omega^2}$$

with $j^2 = -1$

Relaxation frequency: $f_0 = \frac{1}{2\pi \times R \times C}$

as $\omega_i = \frac{1}{R_i \times C_i}$ and $f_i = \frac{\omega_i}{2\pi}$ then $R_i^2 \times C_i^2 \times \omega^2 = \left(\frac{f}{f_i}\right)^2$

Theoretical approach



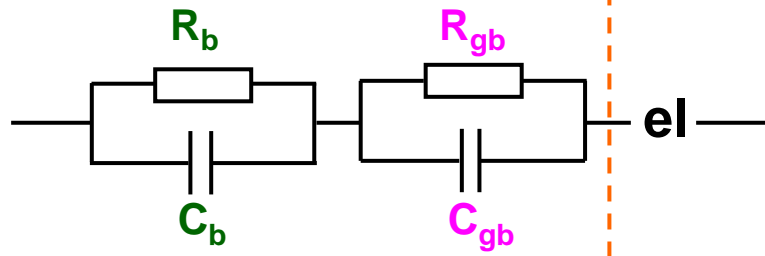
$$Z_{R//C} = \frac{R_i}{1 + (f/f_i)^2} - j \frac{(f/f_i) \times R_i}{1 + (f/f_i)^2}$$

with $j^2 = -1$

$f_i = f_o^{(i)}$ is the relaxation frequency associated with the phenomenon i

with $f_i = \frac{\omega_i}{2\pi}$; $\omega_i = \frac{1}{R_i \times C_i}$; $\tau_i = R_i \times C_i$

system \equiv electrolyte material



$$Z_{\text{system}} = Z' - jZ'' = Z_{R_b//C_b} + Z_{R_{gb}//C_{gb}}$$

$$Z' = \frac{R_b}{1 + (f/f_b)^2} + \frac{R_{gb}}{1 + (f/f_{gb})^2}$$

and

$$Z'' = \frac{(f/f_b) \times R_b}{1 + (f/f_b)^2} + \frac{(f/f_{gb}) \times R_{gb}}{1 + (f/f_{gb})^2}$$

Theoretical approach

$$L(\theta) = \log\left(\frac{Z'}{Z''}\right) = \log\left(\frac{\left(R_b / \left(1 + (f/f_b)^2\right)\right) + \left(R_{gb} / \left(1 + (f/f_{gb})^2\right)\right)}{\left((f/f_b) \times R_b / \left(1 + (f/f_b)^2\right)\right) + \left((f/f_{gb}) \times R_{gb} / \left(1 + (f/f_{gb})^2\right)\right)}\right)$$

Semi-circles in the Nyquist plane
(relaxation frequencies of R//C
parallel circuits)



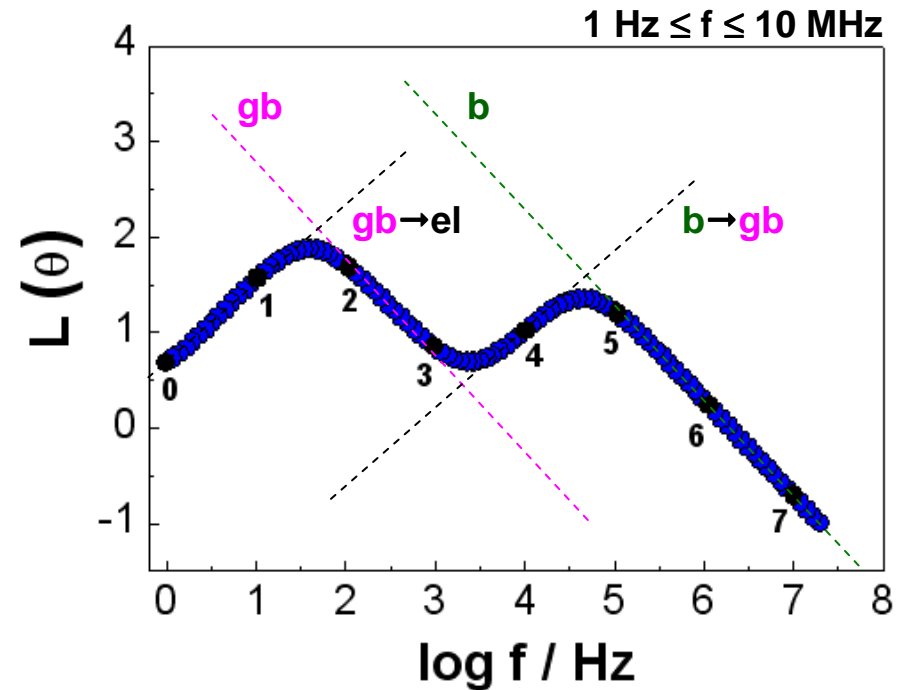
2 straight lines with slope -1

2 straight lines with slope +1

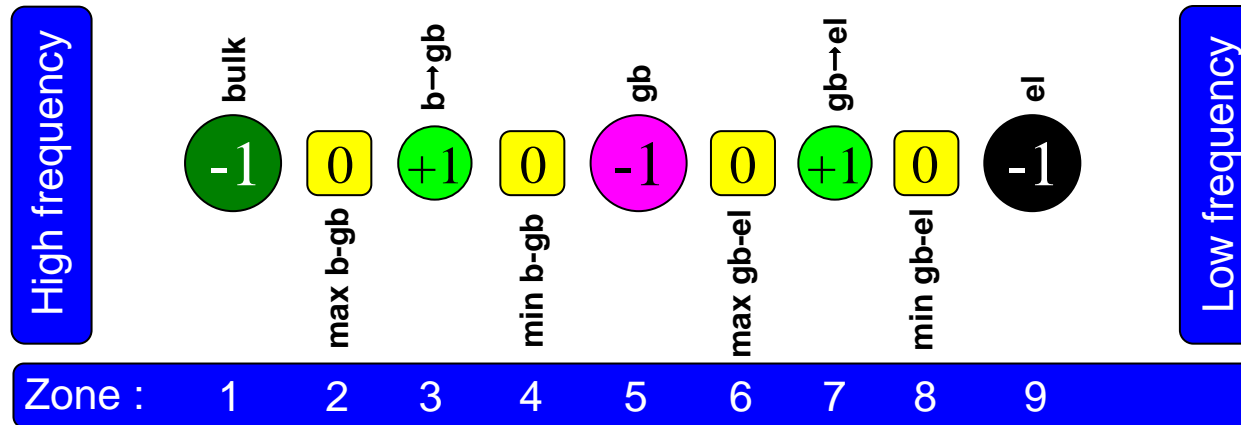


Transition zones (between two
processes i)

First case : $\frac{f_b}{f_{gb}} = 1000$



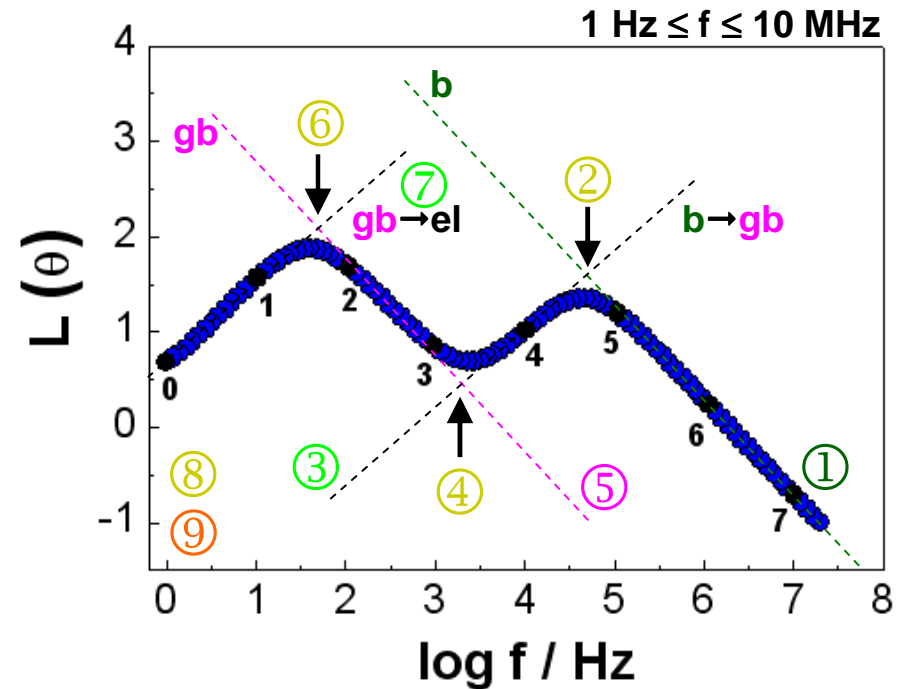
Theoretical approach and discussion



Sample in between 2 electrodes



9 characteristic zones on the $L(\theta) = f(\log f)$ representation



Equation associated with each zone

- ① Straight line with slope -1 (high frequency) $f \gg f_{gb} \gg f_{el}$

$$L(\theta) \approx \log\left(\frac{R_b}{R_b/f_b}\right) - \log(f)$$



$$L(\theta) = \log(f_b) - \log(f)$$

$$L(\theta) = (\lambda_\theta) + (\alpha_\theta) \times \log(f)$$



2 new representations



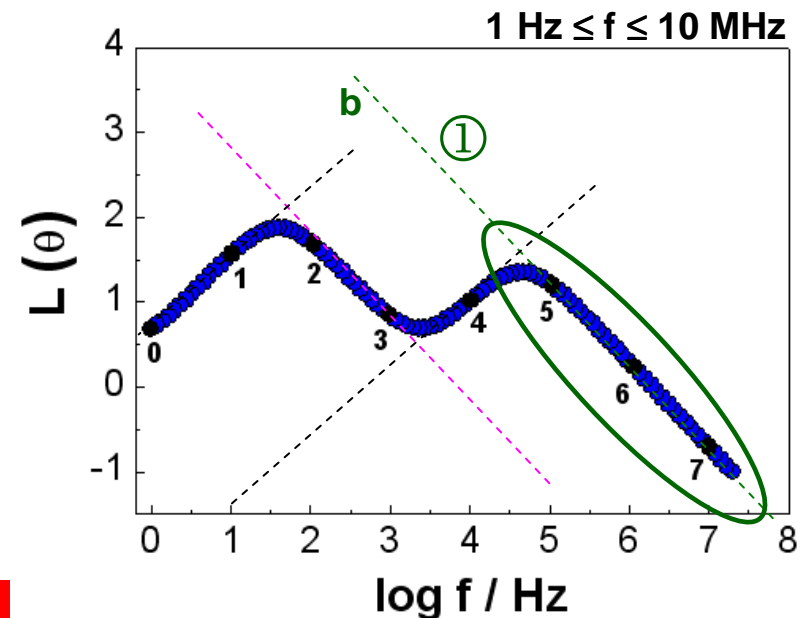
$$(\alpha_\theta) = f(\log(f))$$

slope of the function $L(\theta)$



$$(\lambda_\theta) = f(\alpha_\theta)$$

intercept of the function $L(\theta)$

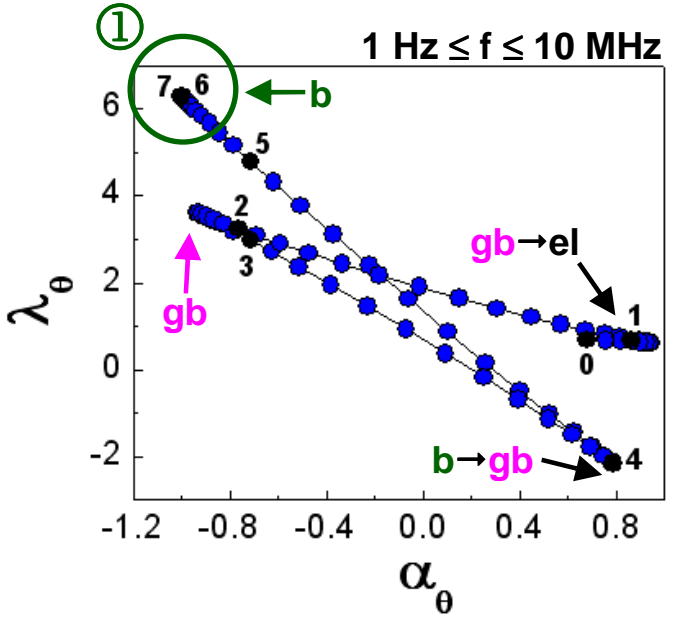
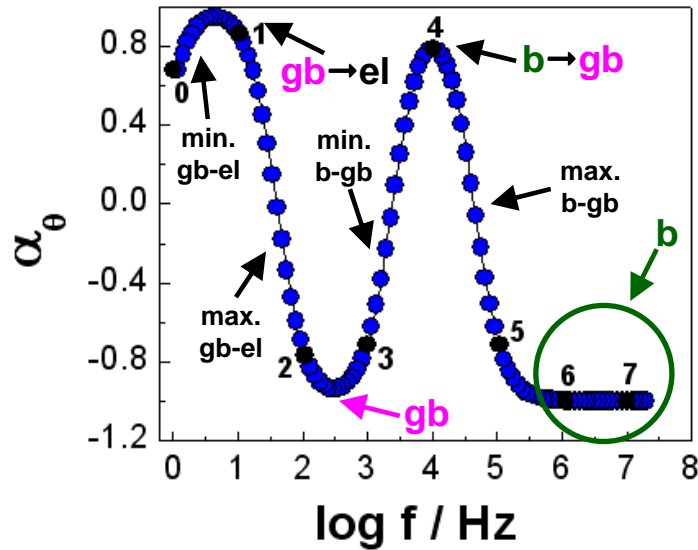


$$\alpha_\theta = \frac{d\log(\theta)}{d\log(f)} = \left(\frac{\Delta L(\theta)}{\Delta \log(f)} \right)_{\Delta \log(f) \rightarrow 0}$$

Equation associated with each zone

$$(\alpha_\theta) = f(\log(f))$$

$$(\lambda_\theta) = f(\alpha_\theta)$$



① $L(\theta) = \log(f_b) - \log(f)$ \rightarrow

Extrapolated value of λ_θ to slope $\alpha_\theta = -1$



$$\log(f_b) = 6.30$$

Relaxation frequency relative to bulk contribution \leftarrow

Extrapolated and theoretical values

$$\log(f_b) = \log\left(\frac{1}{2\pi \times R_b \times C_b}\right) = 6.30$$



$$R_b \times C_b = 8 \times 10^{-9} \Omega F$$

Equation N°	slope / α_θ	$r_f = 1000$ (exp/th)	$r_f = 100$ (exp/th)	$r_f = 10$ (exp/th)	$r_f = 2$ (exp/th)
1	-1	6.30/6.30	-	-	-
3	+1	-	-	-	-
2	0	-	-	-	-
5	-1	-	-	-	-
4	0	-	-	-	-

$$R_b \times C_b = 8.0 \times 10^{-9}$$

①



1 equation and 2 unknowns

Equation associated with each zone

③ Straight line with slope +1 (b → gb transition)

$$L(\theta) \approx \log \left(\frac{R_b + \left(R_{gb} / (f/f_{gb})^2 \right)}{(f/f_b) \times R_b + \left((f/f_b) \times R_{gb} / (f/f_{gb})^2 \right)} \right)$$

$$f_{gb} \ll f \ll f_b \text{ and } f \gg f_{el}$$

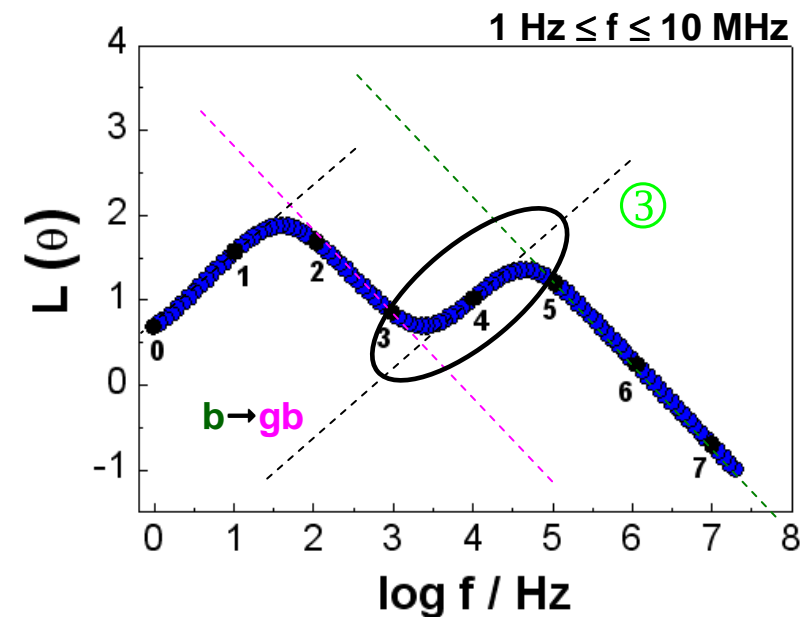
$$\Rightarrow L(\theta) \approx \log \left(\frac{R_b}{R_{gb} \times f_{gb}} \right) + \log(f)$$

$$L(\theta) = (\lambda_\theta) + (\alpha_\theta) \times \log(f)$$



$$\Rightarrow (\lambda_\theta) = \log \left(\frac{R_b}{R_{gb} \times f_{gb}} \right)$$

$$\Rightarrow (\alpha_\theta) = +1$$



Equation associated with each zone

③ Straight line with slope +1 (b→gb transition)

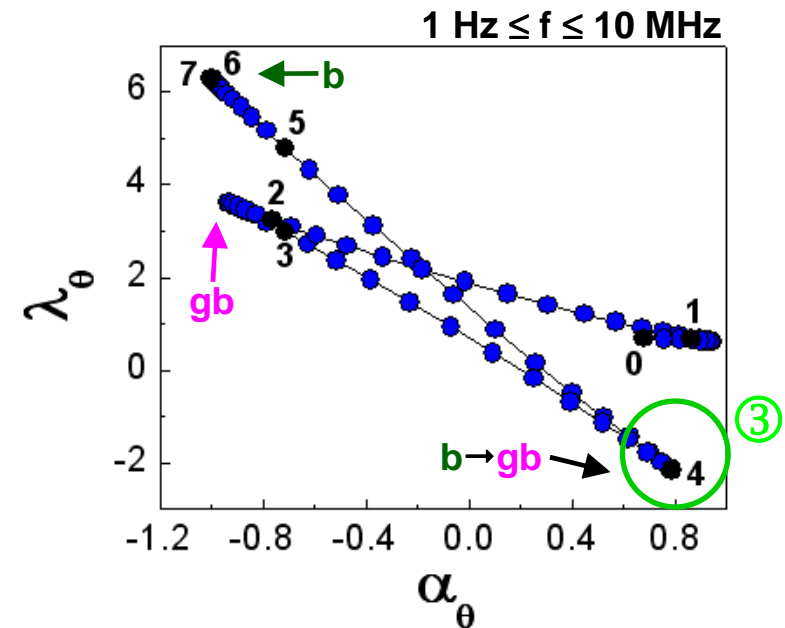
$$L(\theta) \approx \log \left(\frac{R_b + \left(R_{gb} / (f/f_{gb})^2 \right)}{(f/f_b) \times R_b + \left((f/f_b) \times R_{gb} / (f/f_{gb})^2 \right)} \right)$$

$$f_{gb} \ll f \ll f_b \text{ and } f \gg f_{el}$$

➔
$$L(\theta) \approx \log \left(\frac{R_b}{R_{gb} \times f_{gb}} \right) + \log(f)$$

Extrapolated value of λ_θ to slope $\alpha_\theta = +1$

Relation between characteristic parameters of the electrical circuit



Extrapolated and theoretical values

$$\log\left(\frac{R_b}{R_{gb} \times f_{gb}}\right) = -3.00$$



$$2 \times \pi \times R_b \times C_{gb} = 1 \times 10^{-3} \Omega F$$

Equation N°	slope / α_θ	$r_f = 1000$ (exp/th)	$r_f = 100$ (exp/th)	$r_f = 10$ (exp/th)	$r_f = 2$ (exp/th)
1	-1	6.30/6.30	-	-	-
3	+1	-3.00/-3.00	-	-	-
2	0	-	-	-	-
5	-1	-	-	-	-
4	0	-	-	-	-

$$R_b \times C_b = 8.0 \times 10^{-9} \quad \textcircled{1}$$



2 equation and 3 unknowns

$$R_b \times C_{gb} = 1.6 \times 10^{-4} \quad \textcircled{3}$$

Equation associated with each zone

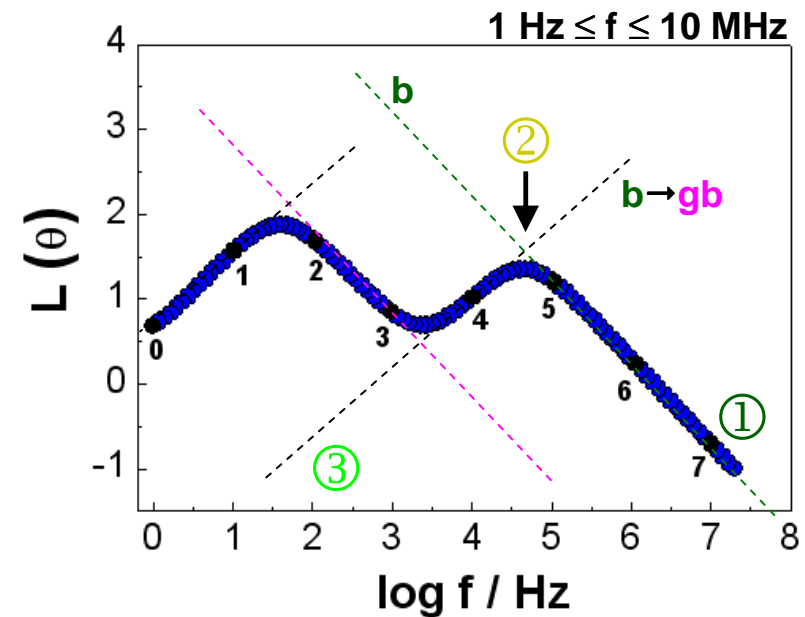
② Maximum between bulk and grain boundaries with slope 0

$$\textcircled{1} \quad \log(f_b) - \log(f_{b \rightarrow gb}^{\max}) = \log\left(\frac{R_b}{R_{gb}} \times \frac{1}{f_{gb}}\right) + \log(f_{b \rightarrow gb}^{\max}) \quad \textcircled{3}$$

$$\longrightarrow \log(f_{b \rightarrow gb}^{\max}) = \frac{1}{2} \times \log\left(f_b \times f_{gb} \times \frac{R_{gb}}{R_b}\right) \longrightarrow \log(f_{b \rightarrow gb}^{\max}) = 4.60$$

Intercept between the straight line of slope -1 (b process) with the straight line of slope +1 (b → gb transition)

Relation between characteristic parameters of the electrical circuit



Extrapolated and theoretical values

$$\frac{1}{2} \times \log \left(f_b \times f_{gb} \times \frac{R_{gb}}{R_b} \right) = 4.60 \quad \longrightarrow \quad \frac{1}{4 \times \pi^2 \times R_b^2 \times C_b \times C_{gb}} = 1.6 \times 10^9 \Omega^{-2} F^{-2}$$

Equation N°	slope / α_θ	$r_f = 1000$ (exp/th)	$r_f = 100$ (exp/th)	$r_f = 10$ (exp/th)	$r_f = 2$ (exp/th)
1	-1	6.30/6.30	-	-	-
3	+1	-3.00/-3.00	-	-	-
2	0	4.60/4.65	-	-	-
5	-1	-	-	-	-
4	0	-	-	-	-

$$R_b \times C_b = 8.0 \times 10^{-9} \quad \textcircled{1}$$

$$R_b \times C_{gb} = 1.6 \times 10^{-4} \quad \textcircled{3}$$

$$R_b^2 \times C_b \times C_{gb} = 1.6 \times 10^{-11} \quad \textcircled{2}$$



3 equations and 3 unknowns

R_b , C_b , C_{gb} can be deduced

$\textcircled{2} \longrightarrow R_{gb}$

Equation associated with each zone

⑤ Straight line with slope -1 (intermediate frequency)

$$L(\theta) \approx \log \left(\frac{R_b + (1 + (1/f_{gb})^2)}{(f/f_b) \times R_b + ((f/f_b) \times R_{gb} / (1 + (f/f_{gb})^2))} \right) \quad f_{el} \ll f \ll f_b \text{ and } f < f_{gb}$$

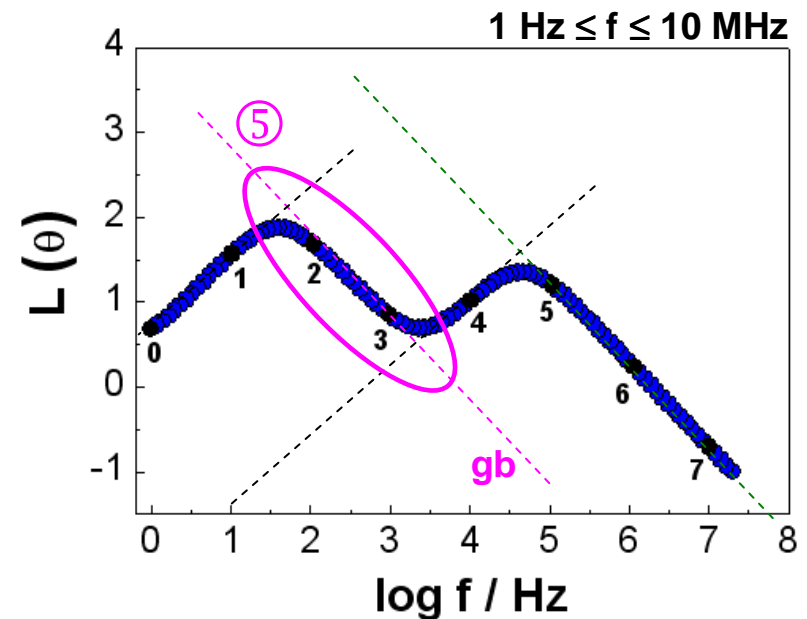
$$\Rightarrow L(\theta) \approx \log \left(\frac{R_b + R_{gb}}{(R_b/f_b) + (R_{gb}/f_{gb})} \right) - \log(f)$$

$$L(\theta) = (\lambda_\theta) + (\alpha_\theta) \times \log(f)$$



$$\Rightarrow (\lambda_\theta) = \log \left(\frac{R_b + R_{gb}}{(R_b/f_b) + (R_{gb}/f_{gb})} \right)$$

$$\Rightarrow (\alpha_\theta) = -1$$



Equation associated with each zone

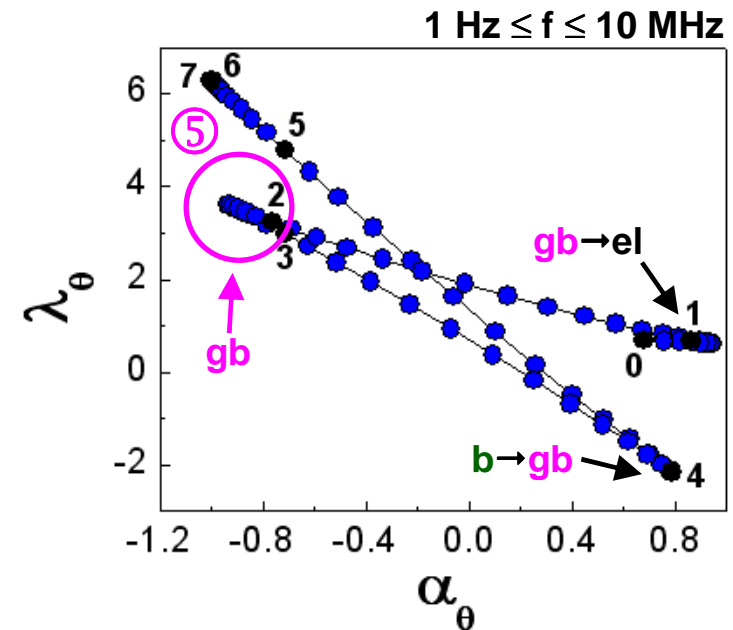
- ⑤ Straight line with slope -1 (intermediate frequency)

$$L(\theta) \approx \log \left(\frac{R_b + (1 + (1/f_{gb})^2)}{(f/f_b) \times R_b + ((f/f_b) \times R_{gb} / (1 + (f/f_{gb})^2))} \right) \quad f_{el} \ll f \ll f_b \text{ and } f < f_{gb}$$

➔
$$L(\theta) \approx \log \left(\frac{R_b + R_{gb}}{(R_b/f_b) + (R_{gb}/f_{gb})} \right) - \log(f)$$

Extrapolated value of λ_θ to slope $\alpha_\theta = -1$

Relation between characteristic parameters of the electrical circuit



Equation associated with each zone

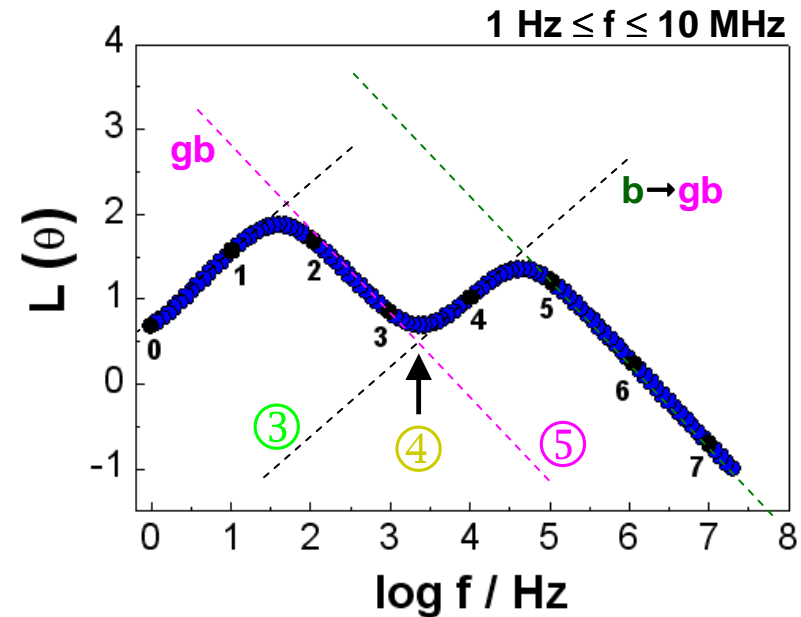
④ Minimum between bulk and grain boundaries with slope 0

$$\textcircled{3} \log\left(\frac{R_b}{R_{gb}} \times \frac{1}{f_{gb}}\right) + \log(f_{b \rightarrow gb}^{\min}) = \log\left(\frac{R_b + R_{gb}}{(R_b/f_b) + (R_{gb}/f_{gb})}\right) - \log(f_{b \rightarrow gb}^{\min}) \quad \textcircled{5}$$

➔
$$\log(f_{b \rightarrow gb}^{\min}) = \frac{1}{2} \times \log\left(\frac{R_{gb}}{R_b} \times f_{gb} \times \left(\frac{R_b + R_{gb}}{(R_b/f_b) + (R_{gb}/f_{gb})}\right)\right)$$

Intercept between the straight line of slope +1 (b→gb transition) with the straight line of slope -1 (gb process)

Relation between characteristic parameters of the electrical circuit



Extrapolated and theoretical values

$$\textcircled{5} \quad \log \left(\frac{R_b + R_{gb}}{2 \times \pi \times (R_b^2 \times C_b + R_{gb}^2 \times C_{gb})} \right) = 3.78$$

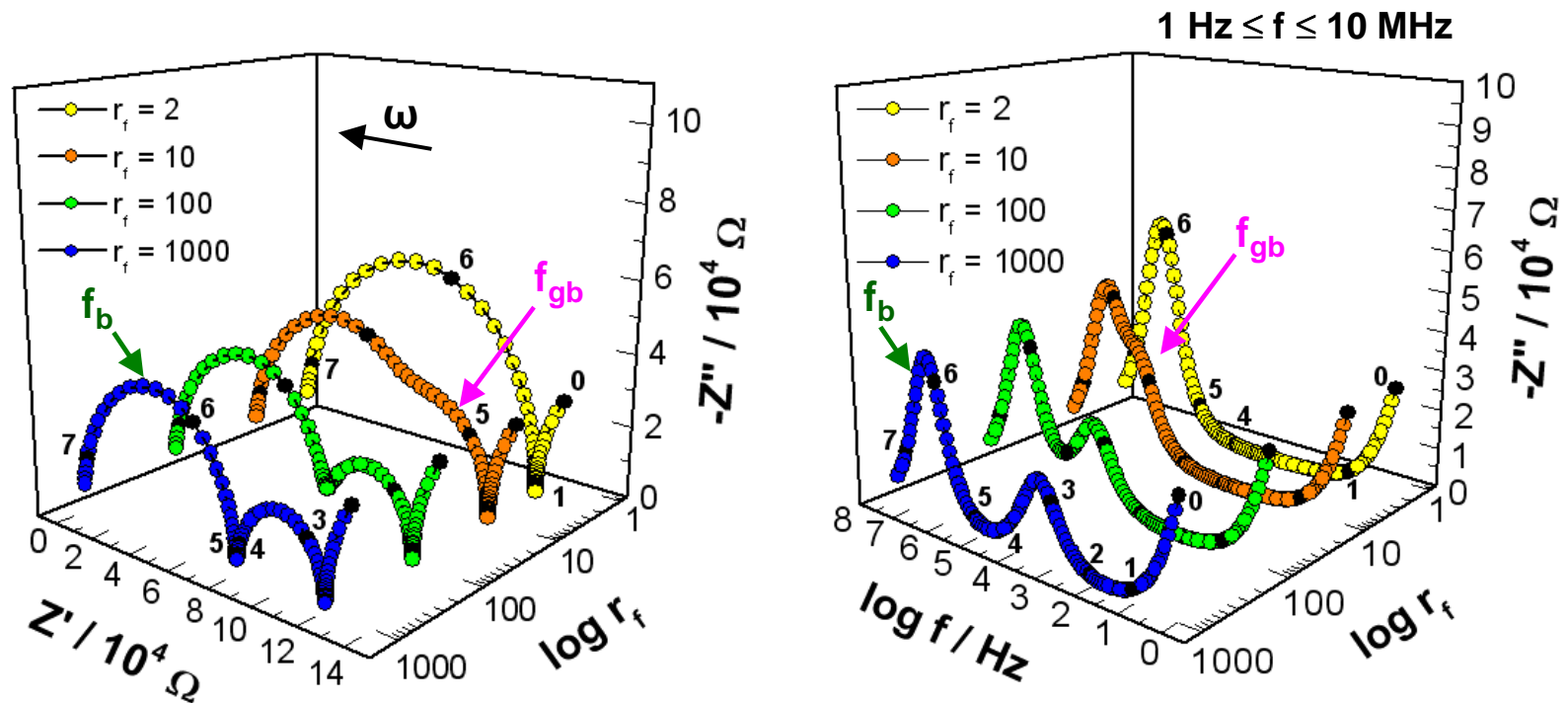
$$\textcircled{4} \quad \frac{1}{2} \times \log \left(\frac{1}{4 \times \pi^2 \times R_b \times C_{gb}} \times \left(\frac{R_b + R_{gb}}{(R_b^2 \times C_b + R_{gb}^2 \times C_{gb})} \right) \right) = 3.40$$

Equation N°	slope / α_θ	$r_f = 1000$ (exp/th)	$r_f = 100$ (exp/th)	$r_f = 10$ (exp/th)	$r_f = 2$ (exp/th)
1	-1	6.30/6.30	-	-	-
3	+1	-3.00/-3.00	-	-	-
2	0	4.60/4.65	-	-	-
5	-1	3.78/3.77	-	-	-
4	0	3.40/3.39	-	-	-



Perfect agreement between the theoretical values and the ones obtained by extrapolation or intercepts points

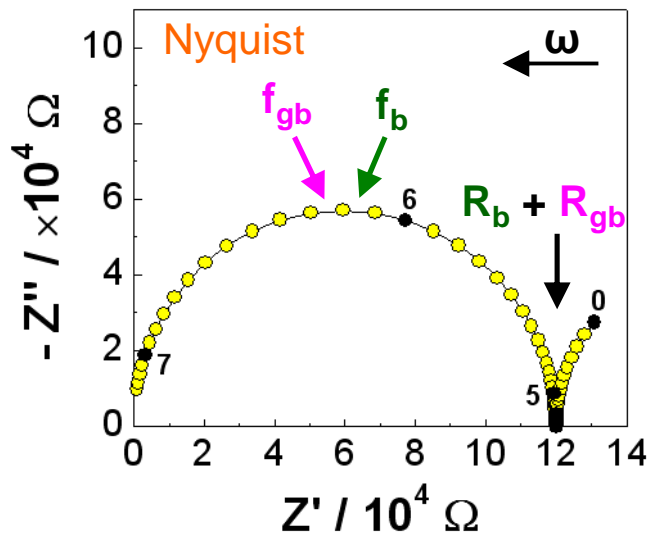
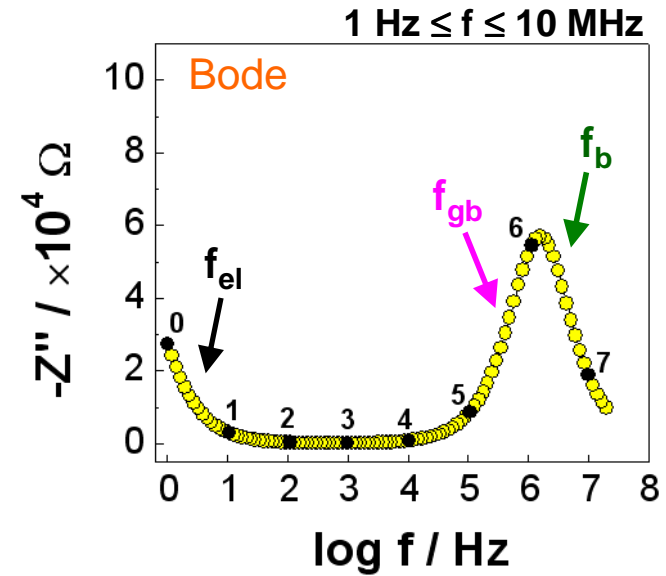
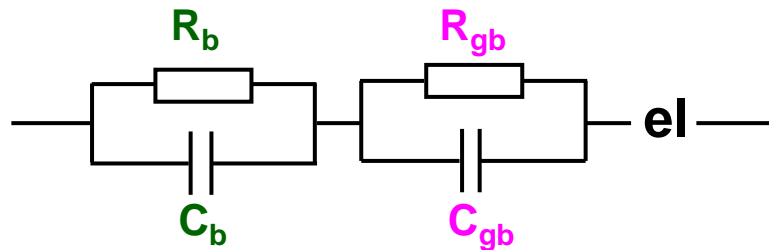
$r_f = f_b/f_{gb}$ dependency of impedance spectra



- ➔ Classical representations do not permit to separate bulk and grain boundaries processes when $r_f < 10$
- ➔ Starting characteristic parameters cannot be extracted for NLLS refinements

Case $r_f = f_b/f_{gb} = 2$

system \equiv electrolyte material



Bulk and grain boundaries processes are strongly overlapped

New complex plane

Case $r_f = f_b/f_{gb} = 2 : L(\theta) = f(\log(f))$

$$L(\theta) = \log\left(\frac{Z'}{Z''}\right) = \log\left(\frac{\left(R_b / \left(1 + (f/f_b)^2\right)\right) + \left(R_{gb} / \left(1 + (f/f_{gb})^2\right)\right)}{\left((f/f_b) \times R_b / \left(1 + (f/f_b)^2\right)\right) + \left((f/f_{gb}) \times R_{gb} / \left(1 + (f/f_{gb})^2\right)\right)}\right)$$

Semi-circles in the Nyquist plane
(relaxation frequencies of R//C
parallel circuits)

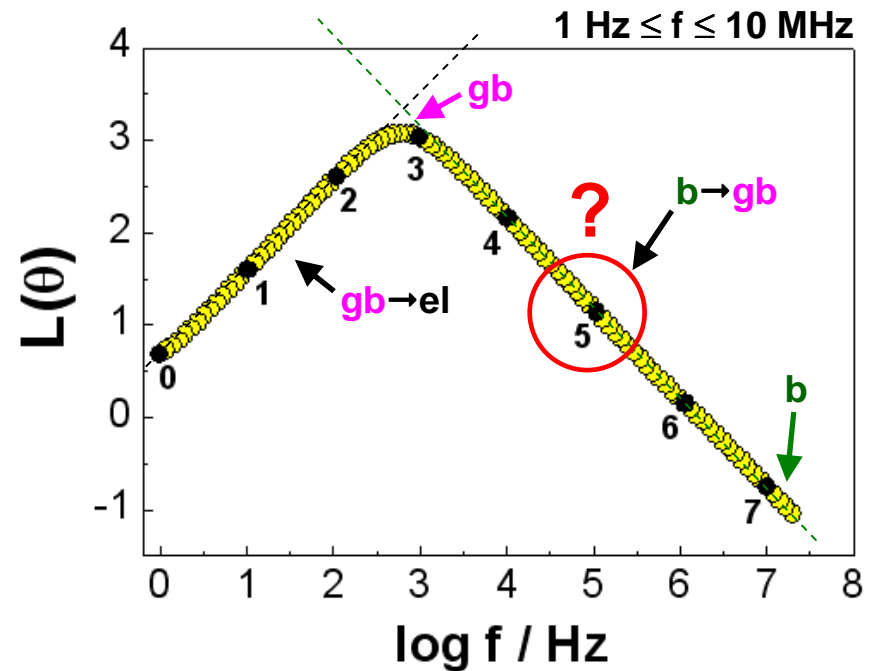


1 straight line with slope -1

1 straight lines with slope +1



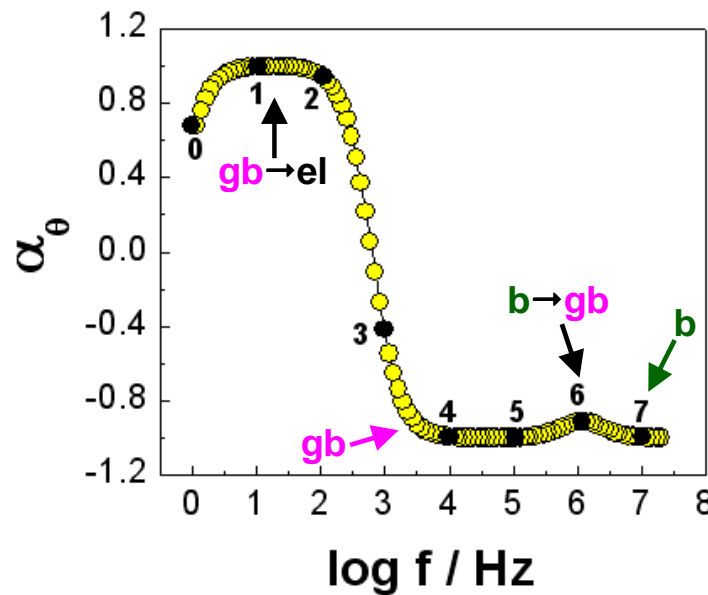
Transition zones (between two
processes i)



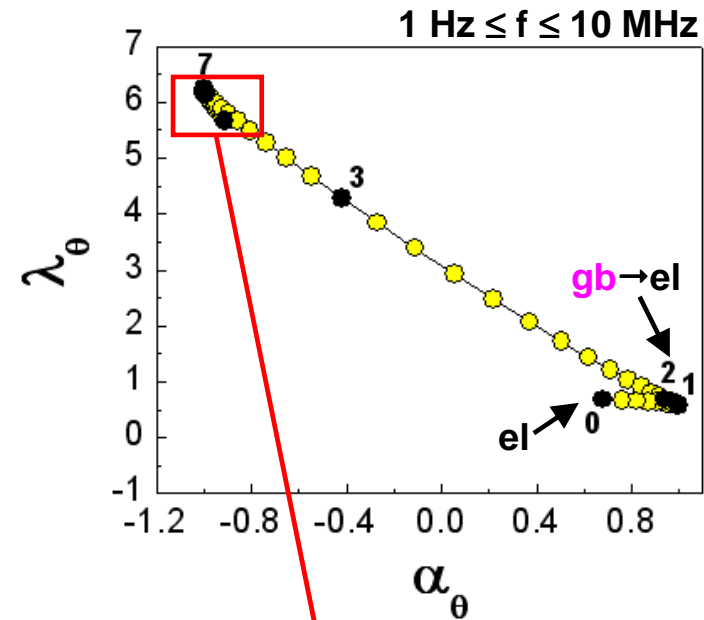
$L(\theta) = f(\log(f))$ not sensitive enough
to detect the $b \rightarrow gb$ transition

Case $r_f = f_b/f_{gb} = 2$

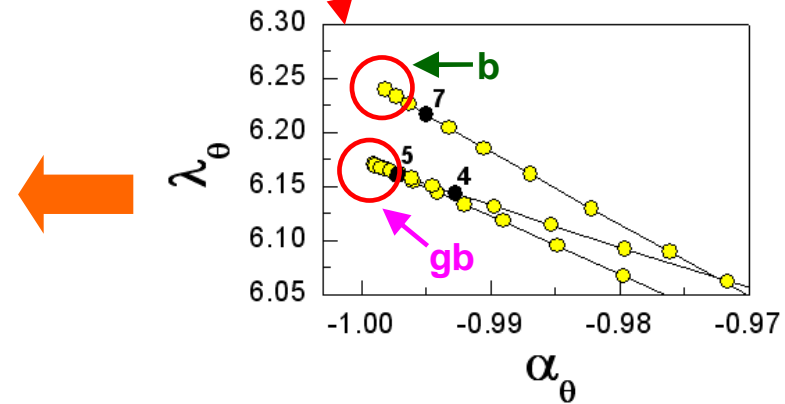
$$(\alpha_\theta) = f(\log(f))$$



$$(\lambda_\theta) = f(\alpha_\theta)$$

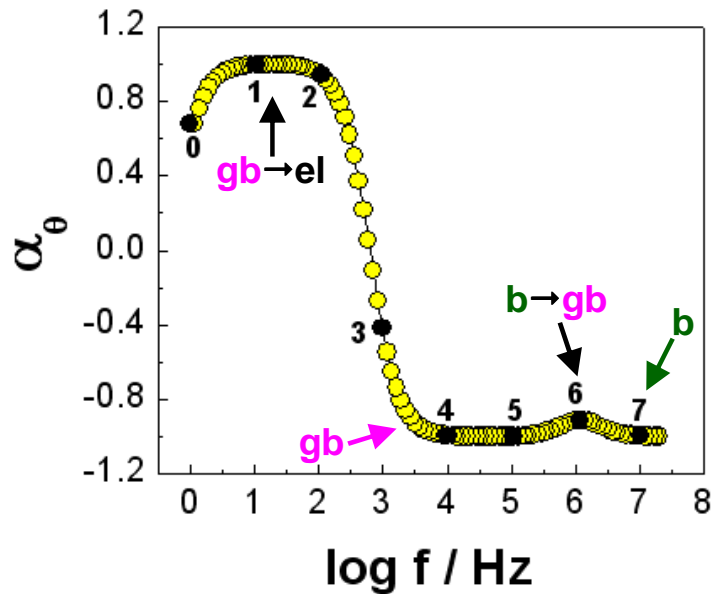


① Bulk (b) and ⑤ grain boundaries (gb) processes can be deconvoluted in the new impedance plane

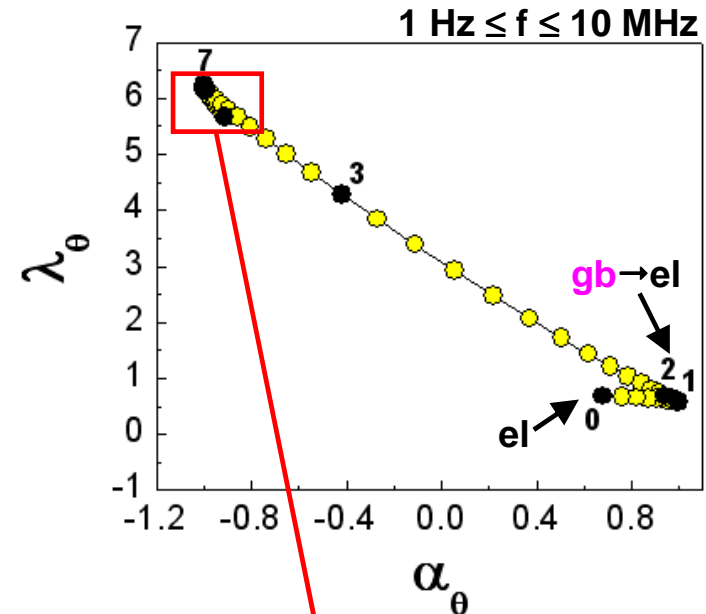


Case $r_f = f_b/f_{gb} = 2$

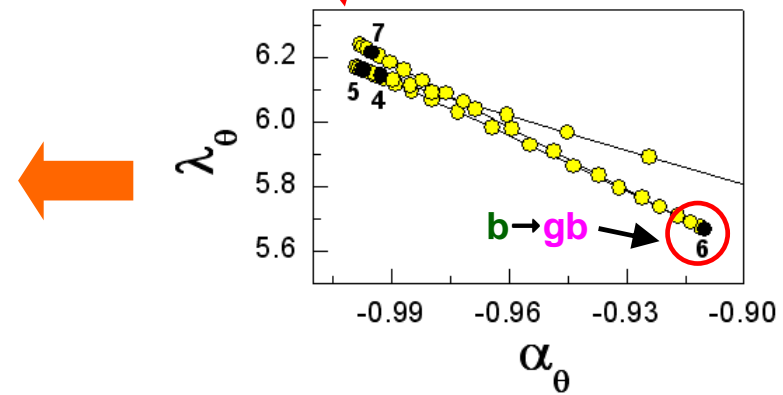
$$(\alpha_\theta) = f(\log(f))$$



$$(\lambda_\theta) = f(\alpha_\theta)$$



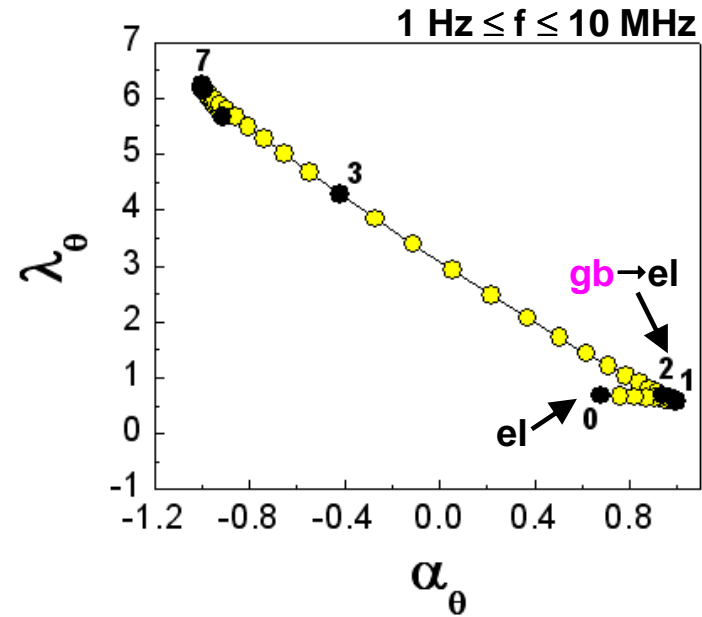
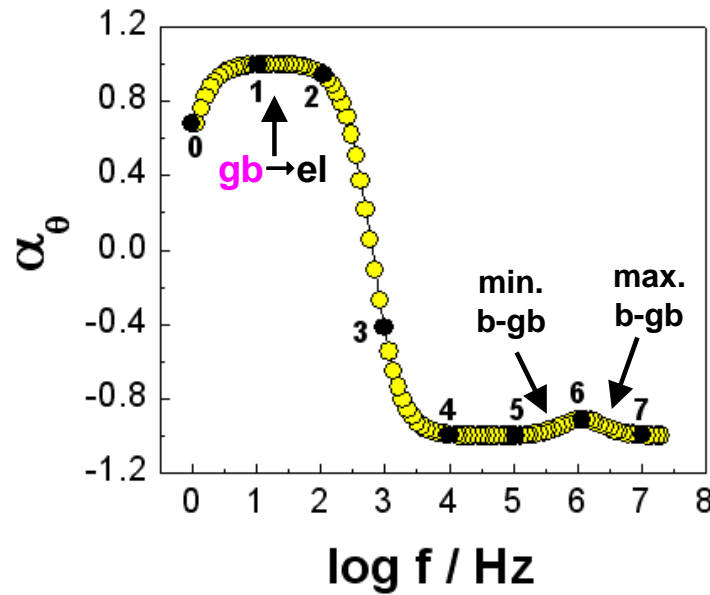
The transition ③ $b \rightarrow gb$ is detected in the $\alpha_\theta = \log(f)$ plane as well as in the $\lambda_\theta = f(\alpha_\theta)$ one



Case $r_f = f_b/f_{gb} = 2$

$$(\alpha_\theta) = f(\log(f))$$

$$(\lambda_\theta) = f(\alpha_\theta)$$



The ② max. b→gb and ④ min. b→gb zones are detected in the $\alpha_\theta = \log(f)$

Values of ② and ④ are deduced using tangents method

Extrapolated and theoretical values : case $r_f = 2$

Equations ① ② ③ ④ and ⑤ can be resolved and then R_b , R_{gb} , C_b , C_{gb} can be extracted even if relaxation frequencies of bulk and grain boundaries processes are very close

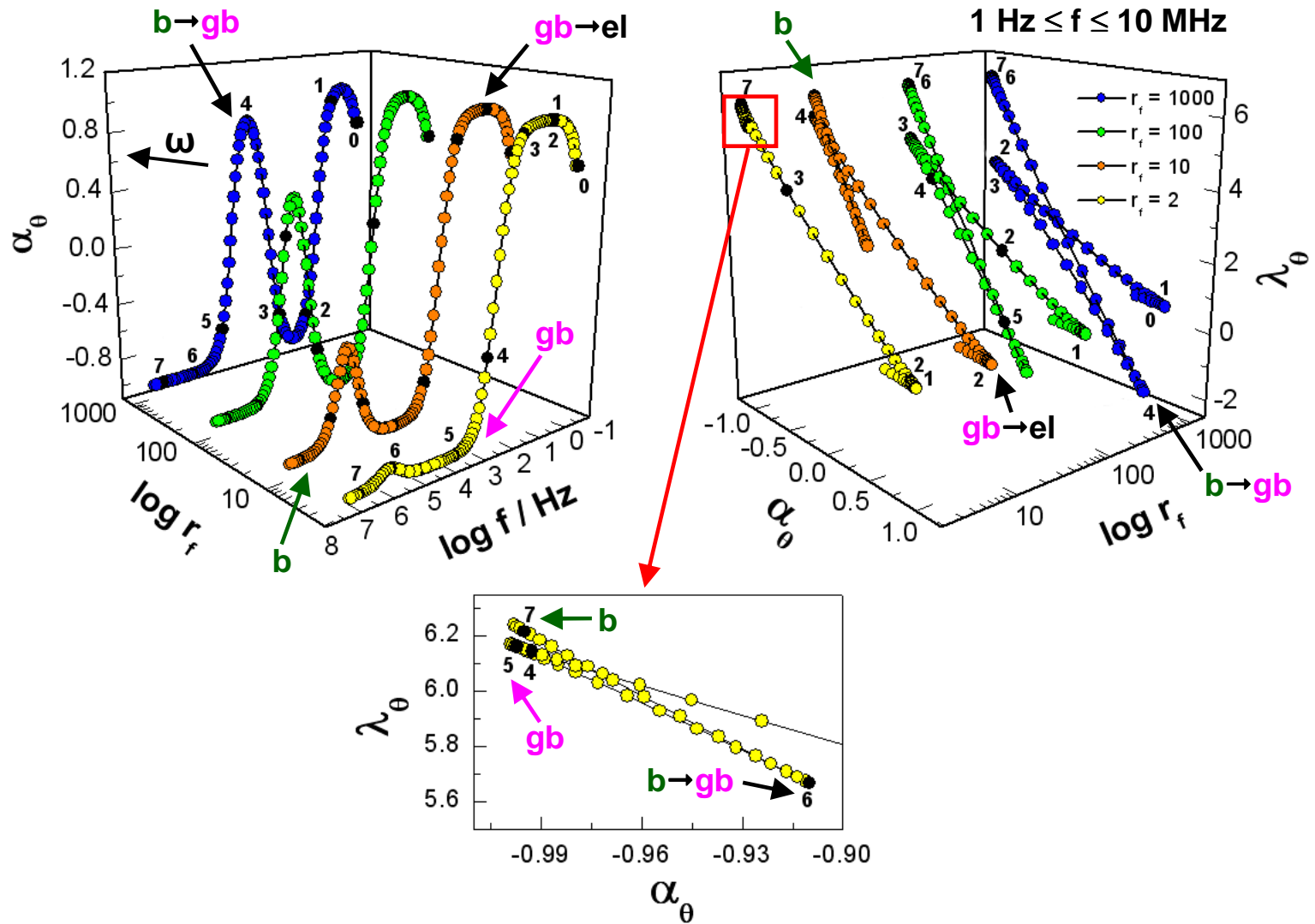


Equation N°	slope / α_θ	$r_f = 1000$ (exp/th)	$r_f = 100$ (exp/th)	$r_f = 10$ (exp/th)	$r_f = 2$ (exp/th)
1	-1	6.30/6.30	-	-	6.30/6.30
3	+1	-3.00/-3.00	-	-	-5.70/-5.70
2	0	4.60/4.65	-	-	6.00/6.00
5	-1	3.78/3.77	-	-	6.17/6.17
4	0	3.40/3.39	-	-	6.00/5.94



Perfect agreement between the theoretical values and the ones obtained by extrapolation or intercepts points

3D graphical representation of $\alpha_\theta = f(\log(f))$ and $\lambda_\theta = f(\alpha_\theta)$



Extrapolated and theoretical values : case $r_f = 10$ and $r_f = 100$

- ① bulk process (b)
- ② maximum between bulk and grain boundaries (max. b→gb)
- ③ transition between bulk and grain boundaries (b→gb)
- ④ minimum between bulk and grain boundaries (min. b→gb)
- ⑤ grain boundaries process (gb)

Equation N°	slope / α_θ	$r_f = 1000$ (exp/th)	$r_f = 100$ (exp/th)	$r_f = 10$ (exp/th)	$r_f = 2$ (exp/th)
1	-1	6.30/6.30	6.30/6.30	6.30/6.30	6.30/6.30
3	+1	-3.00/-3.00	-4.00/-4.00	-5.00/-5.00	-5.70/-5.70
2	0	4.60/4.65	5.20/5.15	5.50/5.80	6.00/6.00
5	-1	3.78/3.77	4.78/4.77	5.70/5.70	6.17/6.17
4	0	3.40/3.39	4.40/4.38	5.50/5.35	6.00/5.94

Perfect agreement between the theoretical values and the ones obtained by extrapolation or intercepts points

Experimental issues

➔ Impedance spectra must be recorded on fully dense samples (> 95% of the theoretical density)

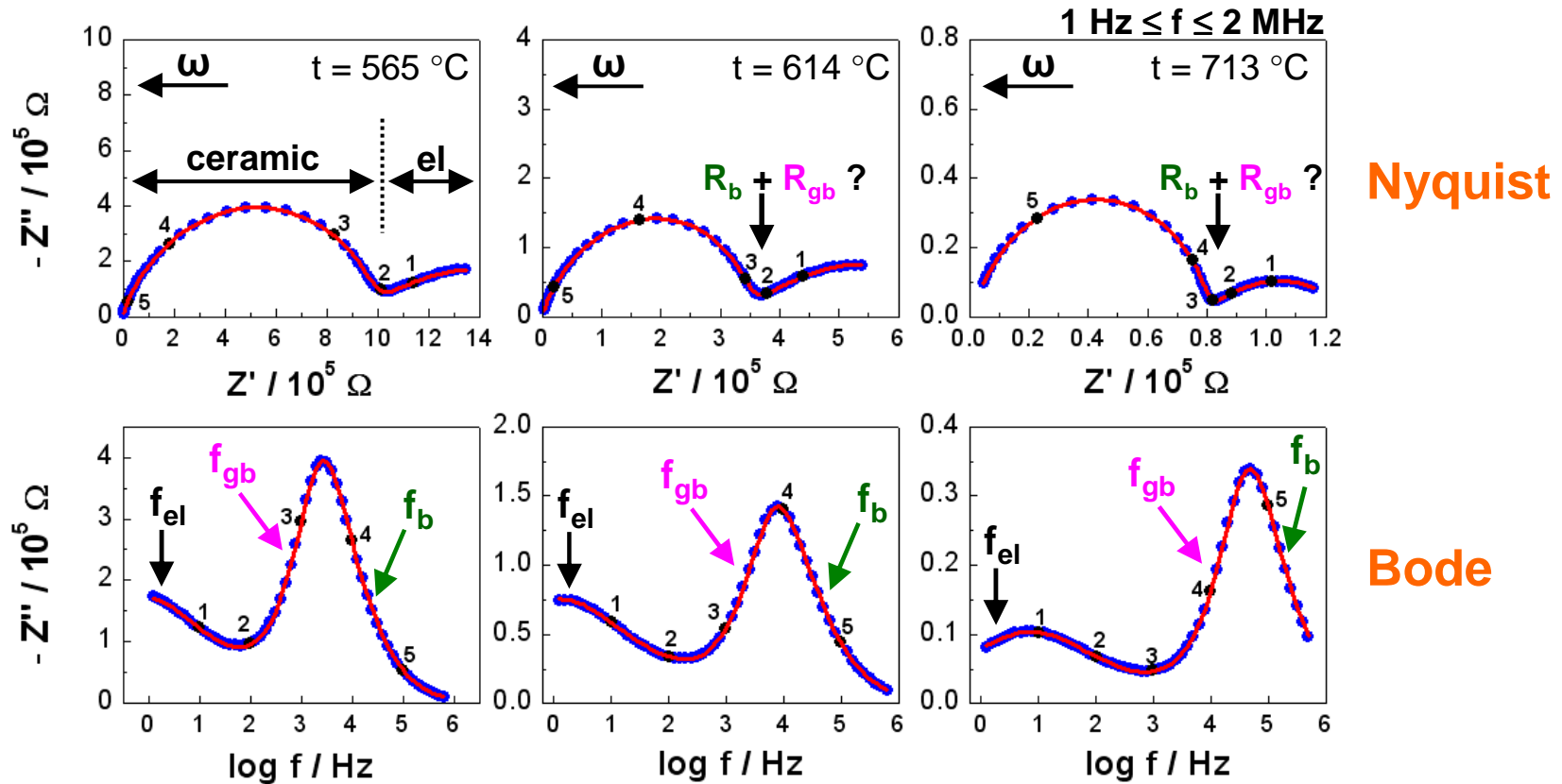
➔
$$\alpha_{\theta} = \frac{d\log(\theta)}{d\log(f)} = \left(\frac{\Delta L(\theta)}{\Delta \log(f)} \right)_{\Delta \log(f) \rightarrow 0}$$

➔ accurate values of α_{θ} if increments of $\Delta \log(f)$ is as small as possible
(12 points per decade of frequency are required)

➔ Application to :

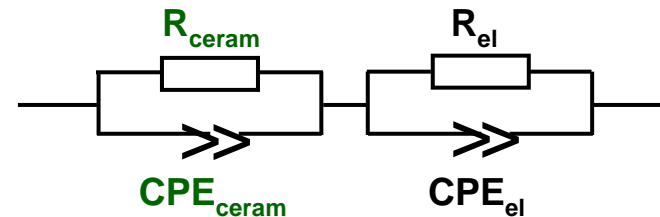
- $\text{Nd}_4\text{Ga}_{2(1-x)}\text{Ti}_{2x}\text{O}_{9+x} \square_{1-x}$ compounds
- $\text{Nd}_{2.955}\text{Sr}_{0.045}\text{O}_{1.9775} \square_{0.0225}(\text{GaO}_4)$

Electrical response of $\text{Nd}_4\text{Ga}_2\text{O}_9$




➔ 2 relaxation phenomena regardless of temperature ?

Equivalent circuit ➔



Impedance of elements : CPE



$$Z_{\text{CPE}}(\omega) = \frac{1}{T \times (j \times \omega)^p} = \frac{R}{(j \times R \times C \times \omega)^p} \quad \text{with} \quad C = \frac{T^{1/p}}{R^{(1-1/p)}}$$

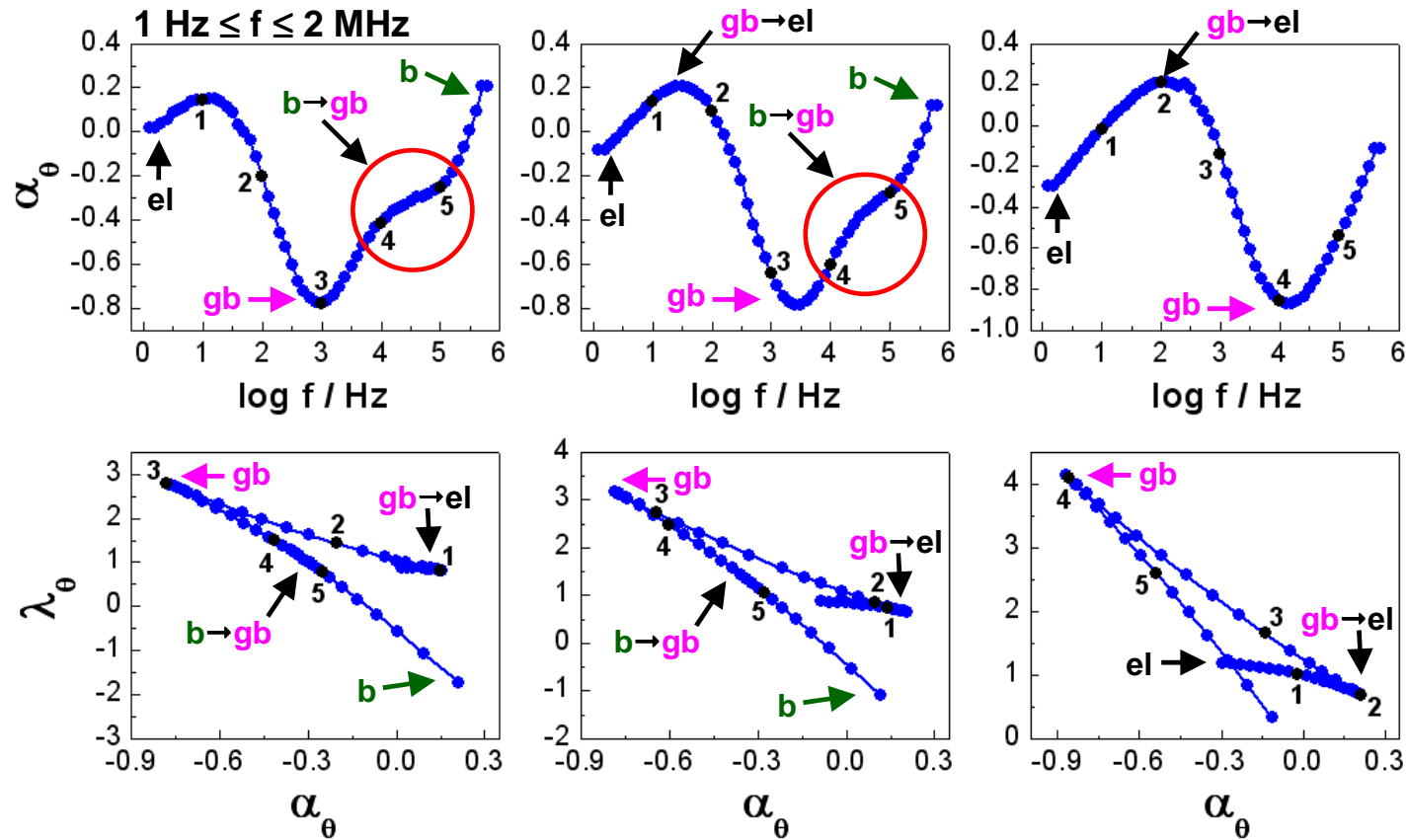
➔ T and p are the characteristic parameters of the CPE

CPE

- Fractal dimension of the material's area
- Electrodes rugosity
- Change in the sample thickness
- Compositional or porosity dispersion inhomogeneity
- Dispersion of activation energy

p	Z' _{CPE} (ω)	Z'' _{CPE} (ω)
-1.0	0	R ² × C × ω = L × ω
-0.5	Z' = Z''	
0	R	0
+0.5	Z' = -Z''	
+1.0	0	

Electrical response of $\text{Nd}_4\text{Ga}_2\text{O}_9$

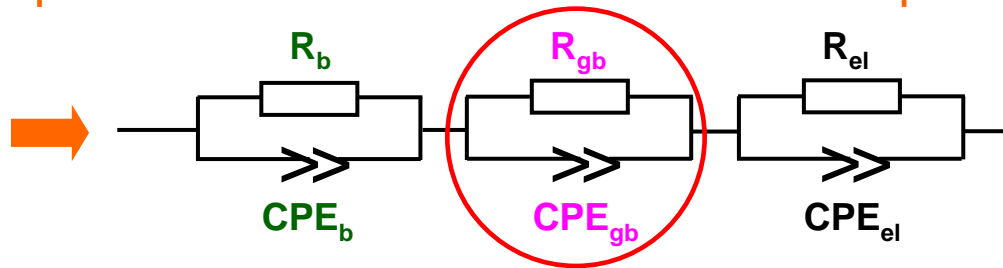


$$\alpha_\theta = f(\log f)$$

$$\lambda_\theta = f(\alpha_\theta)$$

➔ 3 relaxation phenomena are observed at low temperatures

Equivalent circuit ➔



$$\frac{f_b}{f_{gb}} \approx 3$$

Electrical properties of $\text{Nd}_4\text{Ga}_2\text{O}_9$

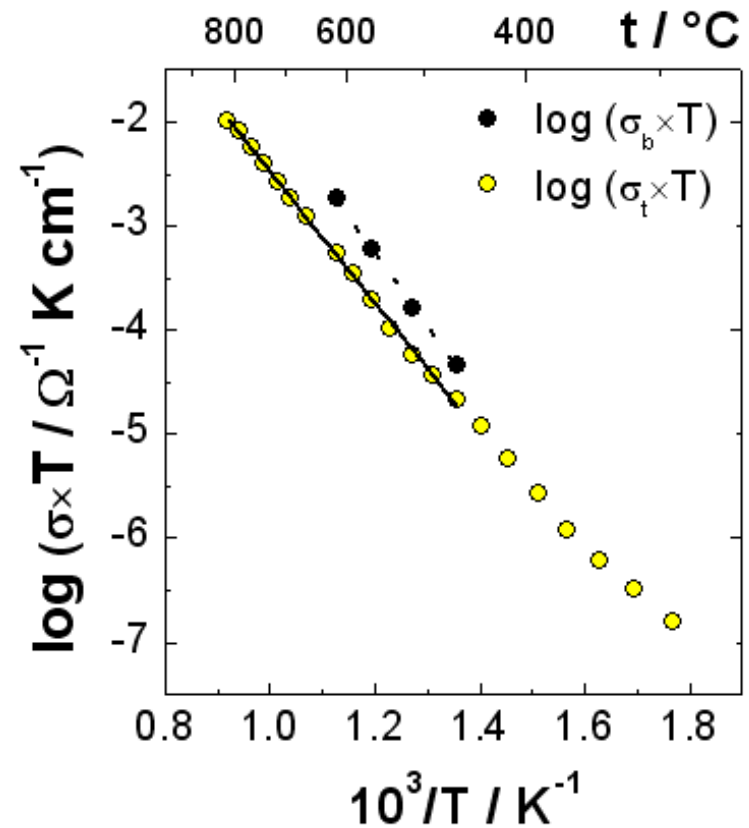
To opte for the electrical circuit
which modelized accurately
experimental data at low
temperatures



Modelisation of impedance
spectra by Non-Linear Least
Squares fitting

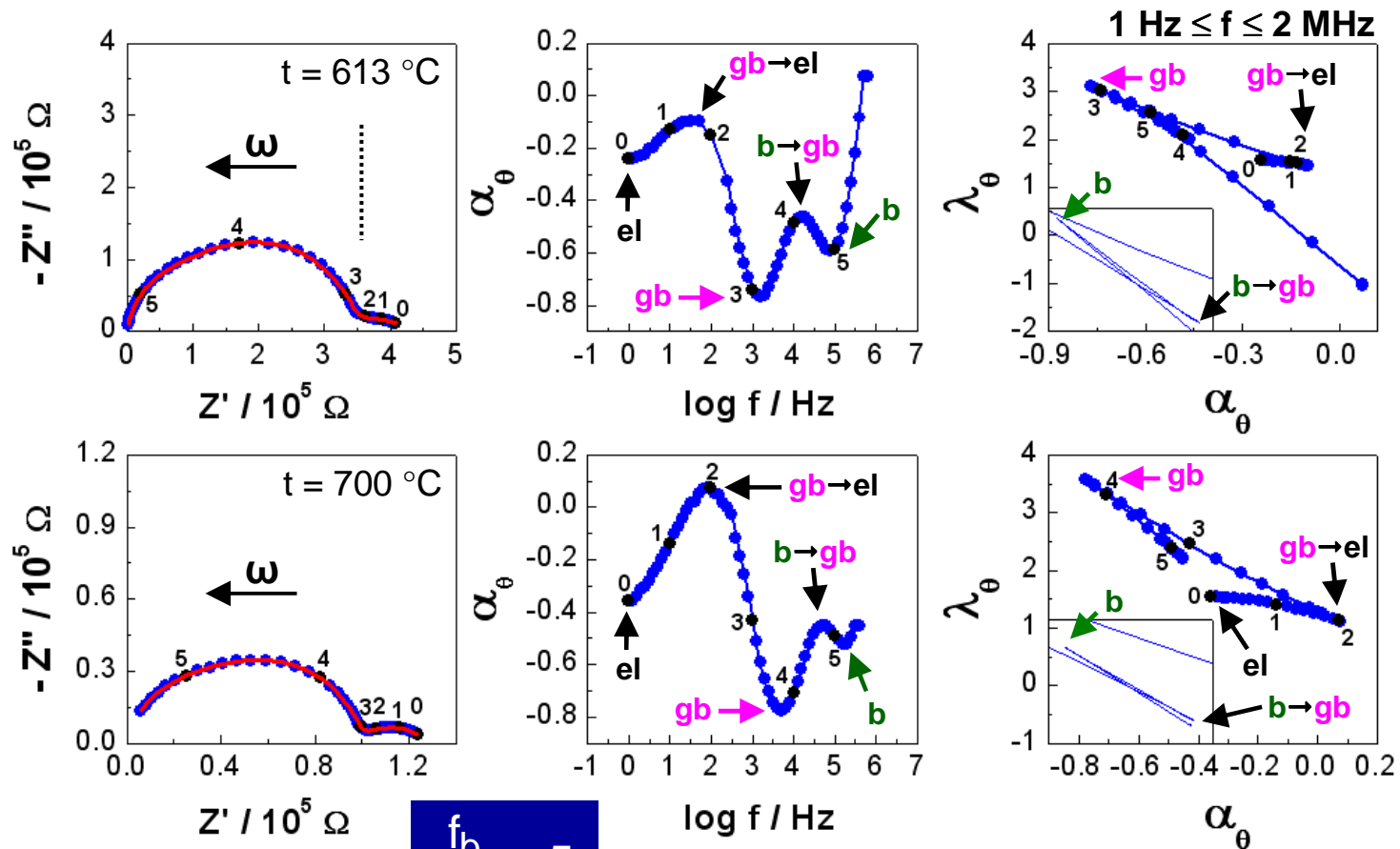


Extraction of R_b , R_{gb} , R_{el} , CPE_b ,
 CPE_{gb} and CPE_{el} starting
parameters



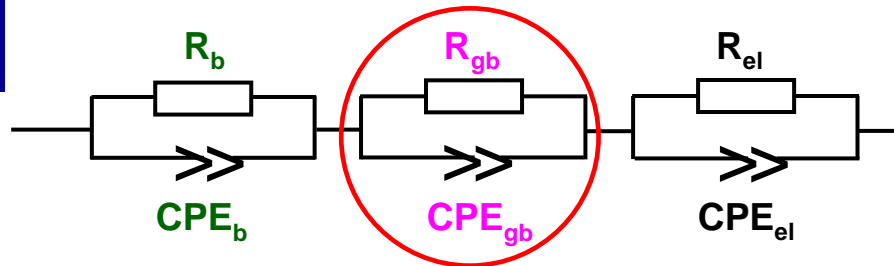
$$\sigma_{\text{bulk}} = 3 \times \sigma_{\text{total}}$$

Electrical response of $\text{Nd}_4\text{Ga}_{1.2}\text{Ti}_{0.8}\text{O}_{9.4}\square_{0.6}$

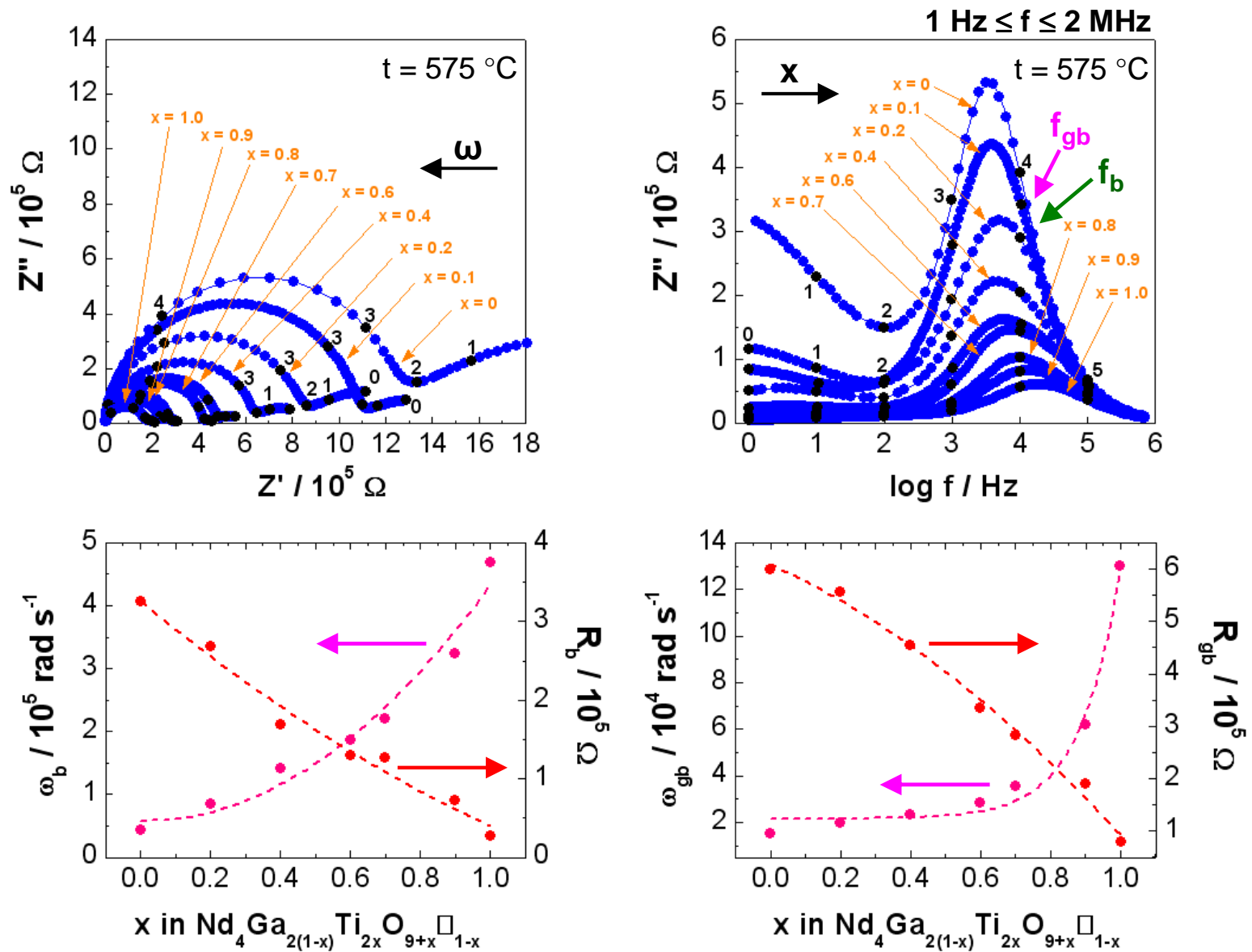


Equivalent circuit

$$\frac{f_b}{f_{gb}} \approx 5$$



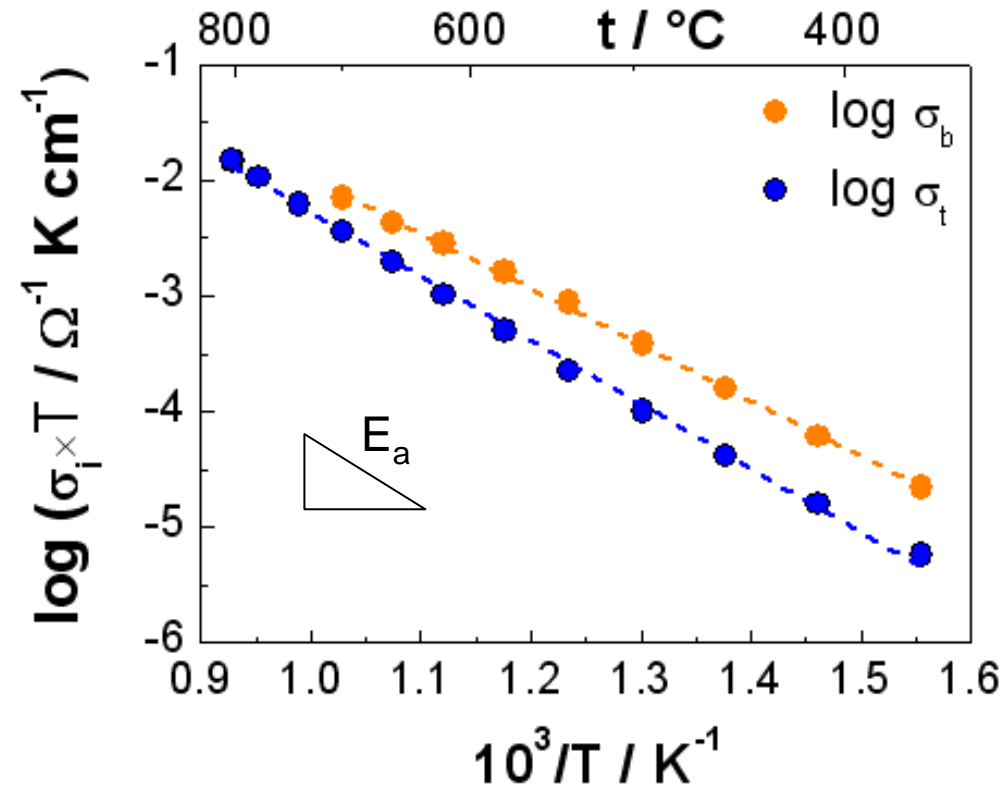
Electrical properties of $\text{Nd}_4\text{Ga}_{2(1-x)}\text{Ti}_{2x}\text{O}_{9+x}\square_{1-x}$



Electrical properties of $\text{Nd}_4\text{Ga}_{2(1-x)}\text{Ti}_{2x}\text{O}_{9+x}\square_{1-x}$

x	i	$R_i / \text{k}\Omega$	C_i / pF	p_i	$\beta_i / ^\circ$	$\omega_i / \text{rad s}^{-1}$	ω_b/ω_{gb}
0	b	325(3)	71(1)	0.99(1)	0.90	4.33×10^4	≈ 3
	gb	600(9)	108(8)	0.91(1)	8.1	1.54×10^4	
0.20	b	268(9)	44(4)	0.98(1)	1.8	8.44×10^4	≈ 4
	gb	557(9)	90(9)	0.90(1)	9.	1.99×10^4	
0.40	b	169(1)	43(2)	0.98(1)	2.3	1.42×10^5	≈ 6
	gb	455(9)	95(5)	0.89(1)	10.4	2.32×10^4	
0.60	b	130(3)	41(1)	0.97(1)	2.9	1.87×10^5	≈ 7
	gb	335(5)	104(3)	0.88(1)	10.9	2.86×10^4	
0.70	b	126(3)	36(1)	0.96(1)	3.2	2.20×10^5	≈ 6
	gb	283(4)	99(2)	0.91(1)	8.5	3.57×10^4	
0.90	b	73(1)	44(2)	0.98(1)	1.7	3.23×10^5	≈ 5
	gb	190(3)	85(2)	0.86(1)	12.2	6.19×10^4	
1.00	b	27(1)	79(1)	0.99(1)	0.90	4.69×10^5	≈ 4
	gb	100(9)	77(7)	0.86(1)	12.6	1.30×10^5	

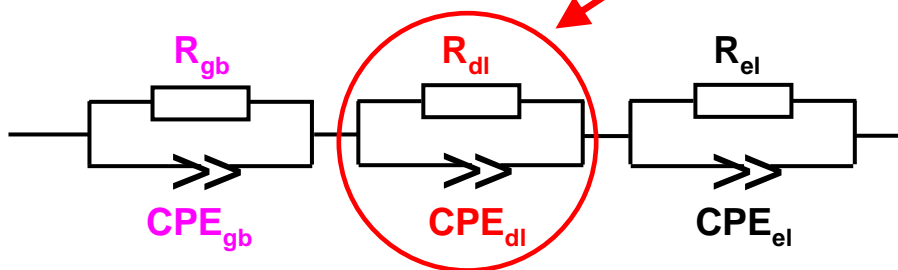
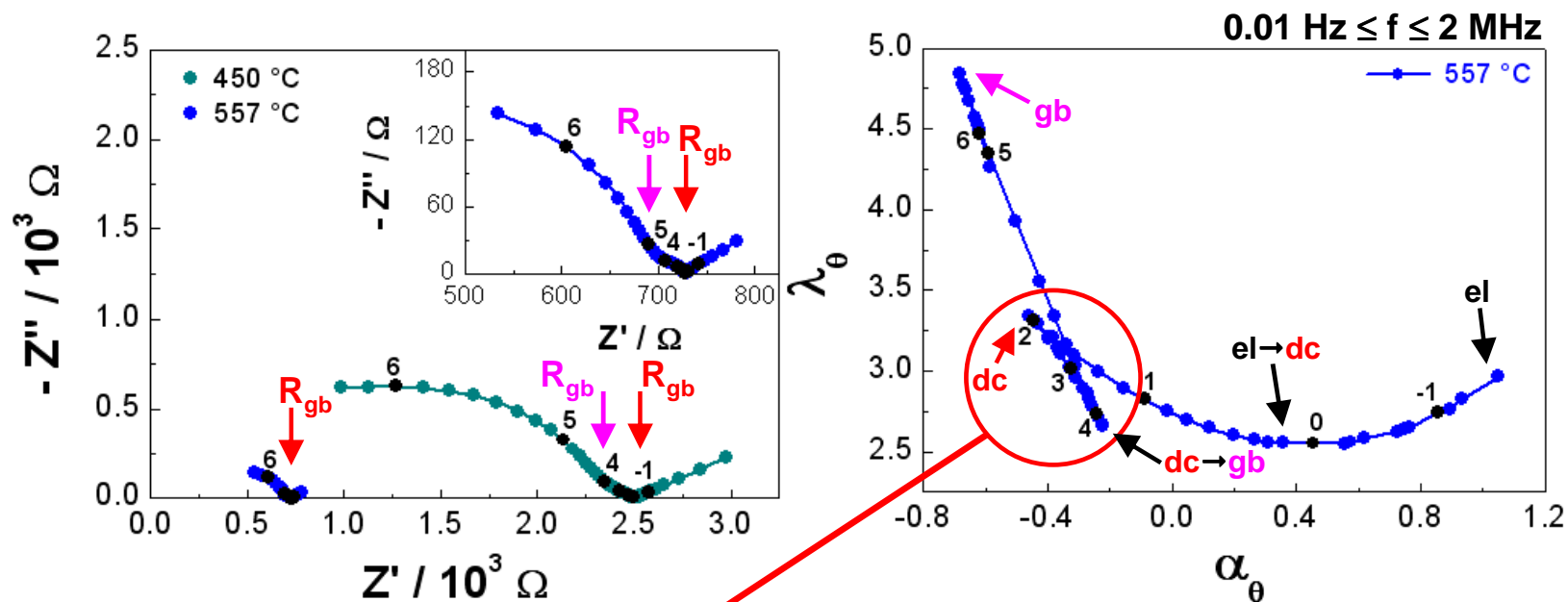
Electrical properties of $\text{Nd}_4\text{Ga}_{0.6}\text{Ti}_{1.4}\text{O}_{9.7}\square_{0.3}$



➔ $(E_a)_{\text{bulk}} = 0.95 \text{ eV}$ vs $(E_a)_{\text{total}} = 1.10 \text{ eV}$

➔ At $700 \text{ }^\circ\text{C}$, $\sigma_{\text{bulk}} = 7.72 \times 10^{-6} \text{ S cm}^{-1}$ vs $\sigma_{\text{total}} = 3.69 \times 10^{-6} \text{ S cm}^{-1}$
i.e. 2 times higher

Electrical response of $\text{Nd}_{2.955}\text{Sr}_{0.045}\text{O}_{1.9775}\square_{0.0225}(\text{GaO}_4)$



Electrical double layer phenomena "dc"
 $10^2 < f(\text{Hz}) < 10^4$



R_{dl} is small
 $C_{dl} \approx 0.40 \mu\text{F cm}^{-2}$

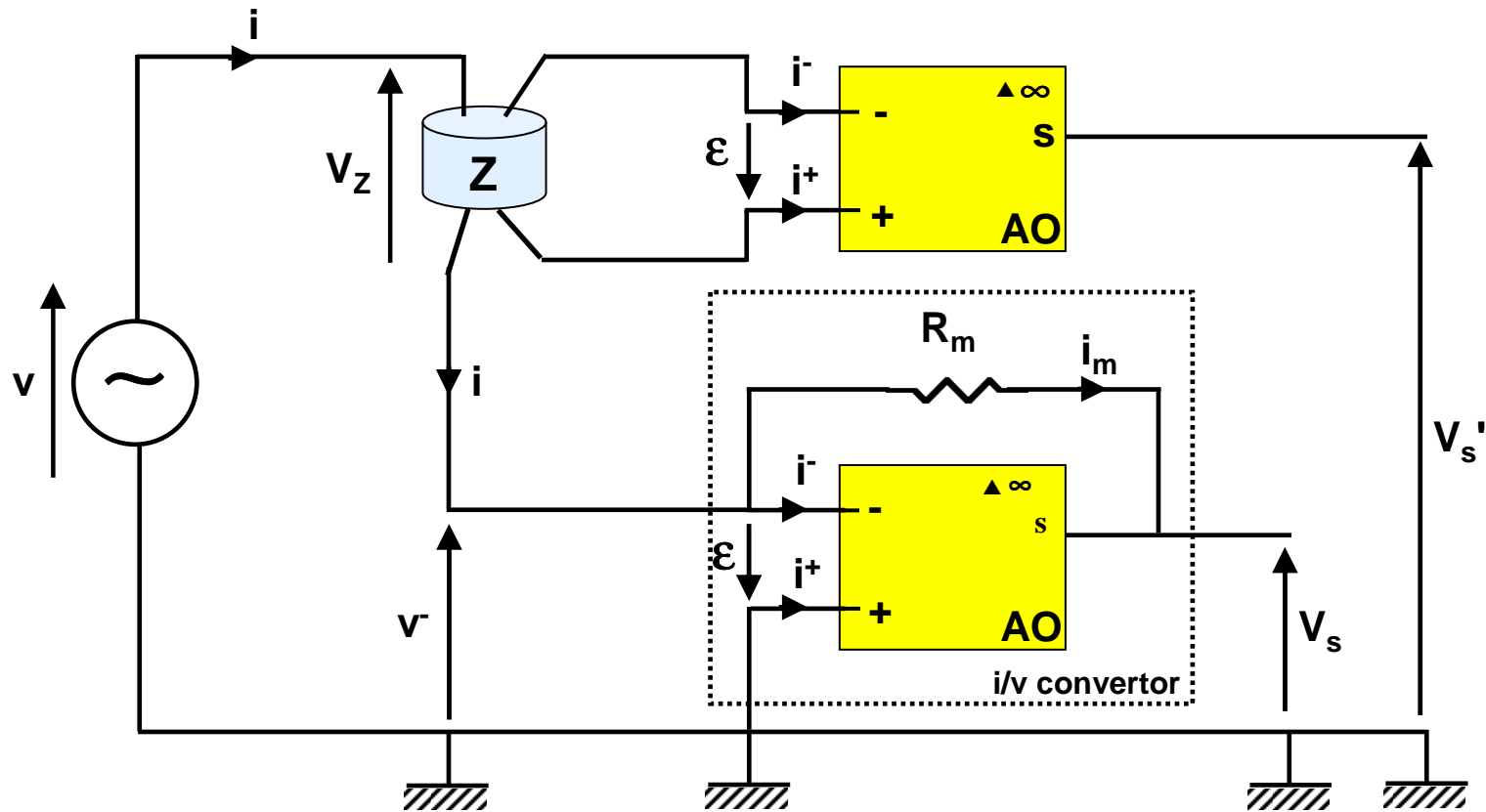


Conclusion

- ➔ Effectiveness of this new representation to separate processes even if their relaxation frequencies are very close
- ➔ Theoretical equations are proposed for each frequency zones of the $\alpha_\theta = f(\log(f))$ and $\lambda_\theta = f(\alpha_\theta)$ representations, giving relationships between the electrical parameters studied
- ➔ All the parameters R_i, C_i, f_i ($i = b, gb$) of these processes can be extracted
 - from this representation and using equations or
 - in combination with the classical ones
- ➔ These parameters can be used as starting parameters for NLLS fitting of impedance spectra
- ➔ Equations can be implemented in NLLS fitting software to limit the possible range of variation of the parameters studied



Annex 1



Annex 2

Solartron 1260 (FRA)

