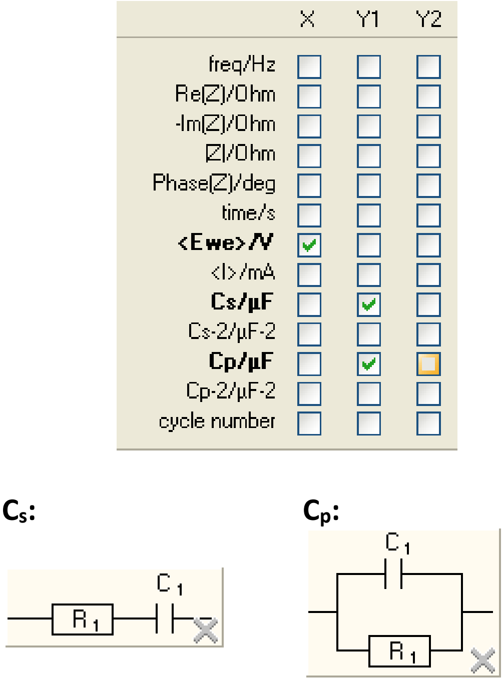
Application of the Capacitance-Voltage curve to photovoltaic cell characterizations

I – INTRODUCTION

Capacitance measurement is widely used to carry out semiconductor characterization such as those for photovoltaic (PV) cells. For example, this measurement is used to determine the doping concentration.

In EC-Lab® & EC-Lab® Express software, it is possible to directly plot the capacitance (directly means without any post-process). The capacitance can be obtained with all the Electrochemical Impedance Spectroscopy (EIS) techniques *i.e.* Potentio EIS (PEIS), Galvano EIS (GEIS), Staircase PEIS (SPEIS), Staircase GEIS (SGEIS), "Wait" technique that allows user to follow up the modulus of Z *vs* time (PEISW) techniques.

Depending on the model circuits considered, two types of capacitance, C_s or C_p, are calculated. The capacitance C_s corresponds to the capacitance of the R+*C* (in **s**eries) circuit and C_p corresponds to the capacitance of the R/*C* (in **p**arallel) circuit (Fig. 1)



	X	Y1	Y2
freq/Hz	☐	☐	☐
Re(Z)/Ohm	☐	☐	☐
-Im(Z)/Ohm	☐	☐	☐
|Z|/Ohm	☐	☐	☐
Phase(Z)/deg	☐	☐	☐
time/s	☐	☐	☐
<Ewe>/V	☑	☐	☐
<I>/mA	☐	☐	☐
Cs/µF	☐	☑	☐
Cs-2/µF-2	☐	☐	☐
Cp/µF	☐	☑	☐
Cp-2/µF-2	☐	☐	☐
cycle number	☐	☐	☐

C_s:

C_p:

Figure 1: The two equivalent circuits offered for direct capacitance plotting.

This note demonstrates how to plot a Capacitance *vs.* Voltage (*C-V*) curve. Firstly, the different options offered to plot the capacitance are shown with a varia-capacitor[1] as an experimental model system. A discussion is given about the selection of the circuit model and a comparison between the capacitance values fitted with ZFit and the capacitance directly available in the technique. Secondly, typical *C-V* characterizations of PV cell are described.

II – EXPERIMENTAL CONDITIONS

Investigations are carried out with a SP-200 equipped with the Ultra Low Current option or with SP-300 and EC-Lab® software. For both systems (*i.e.* varia-capacitor and photovoltaic cell), investigations were carried out with a standard two-electrode connection.

The characteristics of the varia-capacitor are described below:

- low voltage variable capacitance double diode (BB201 from NXP).
- The capacitance is in the range of 10 to 120 pF for a voltage range of 0.5 to 11V.

The *C-V* characterization of the PV cell has been performed on a cell irradiated by a Xenon lamp of 150 W (light source of MOS-200 powered by ALX-150 power supply).

III – VARIA-CAPACITOR INVESTIGATIONS

III - 1 R/C OR R+C EQUIVALENT CIRCUIT?

To choose the appropriate equivalent circuit among R/C or R+C, an EIS measurement on a wide frequency range *i.e.* 3 MHz to 1 mHz is performed. Settings are displayed in Fig. 2.

The EIS measurement leads to a semicircle (Fig. 3), so the R/*C* model (C_p variable) is considered for the *C-V* investigations. The

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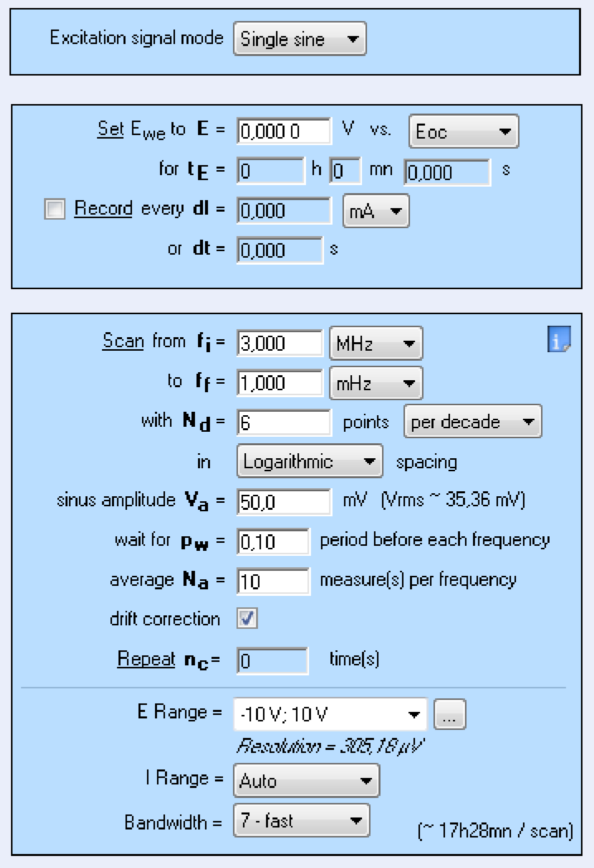
[1] A capacitor whose capacitance may be intentionally and repeatedly changed mechanically or electronically

fitted values of R and *C* are 70 Ohm and 145 pF (Fig. 4), respectively.



Excitation signal mode: Single sine

Set E_{we} to **E** = 0,000 0 V vs. Eoc
for t_E = 0 h 0 mn 0,000 s
☐ Record every **dI** = 0,000 mA
or **dt** = 0,000 s

Scan from f_i = 3,000 MHz
to f_f = 1,000 mHz
with N_d = 6 points per decade
in Logarithmic spacing
sinus amplitude V_a = 50,0 mV (Vrms ~ 35,36 mV)
wait for p_w = 0,10 period before each frequency
average N_a = 10 measure(s) per frequency
drift correction ☑
Repeat n_c = 0 time(s)

E Range = -10 V; 10 V
Resolution = 305,18 µV
I Range = Auto
Bandwidth = 7 - fast
(~ 17h28mn / scan)

Figure 2: Settings for the EIS characterizations of the varia-capacitor.

III - 2 *C-V* INVESTIGATIONS

Two SPEIS techniques are performed. One in the frequency range from 7 MHz to 1 Hz (setting displayed in Fig. 5) and one at one frequency (with similar settings to those shown in Fig. 5 with f_i equal to f_f). Measurements were performed at a frequency of 323 kHz because above this frequency the responses of the varia-capacitor is dependent on the frequency (Fig. 6). The experiments are named SPEIS$_{7MHz\ 1Hz}$ and SPEIS$_{323kHz}$, respectively. The voltage scan starts at 0V and goes up to 10V with steps of 200 mV.

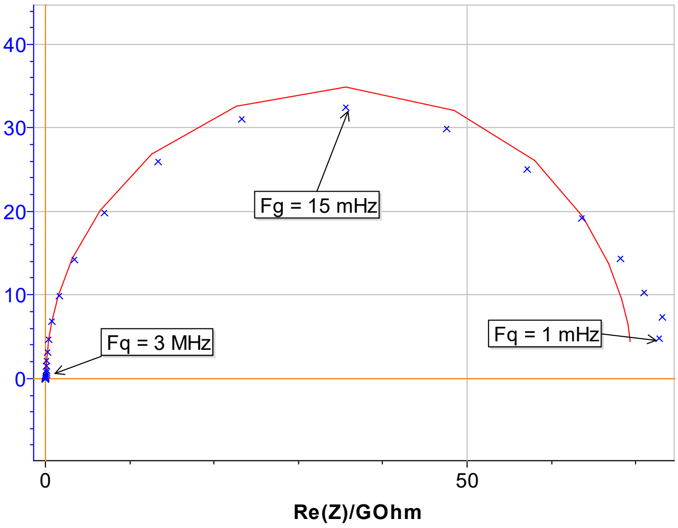
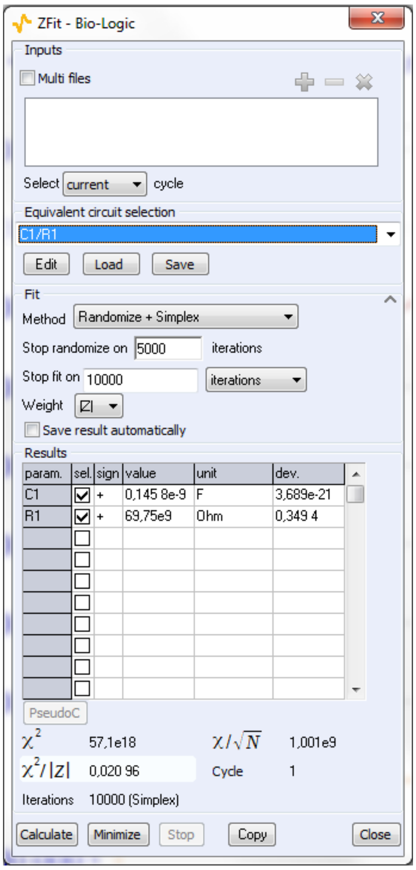


Figure 3: Nyquist plot of varia-capacitor (Exp data fitted data).

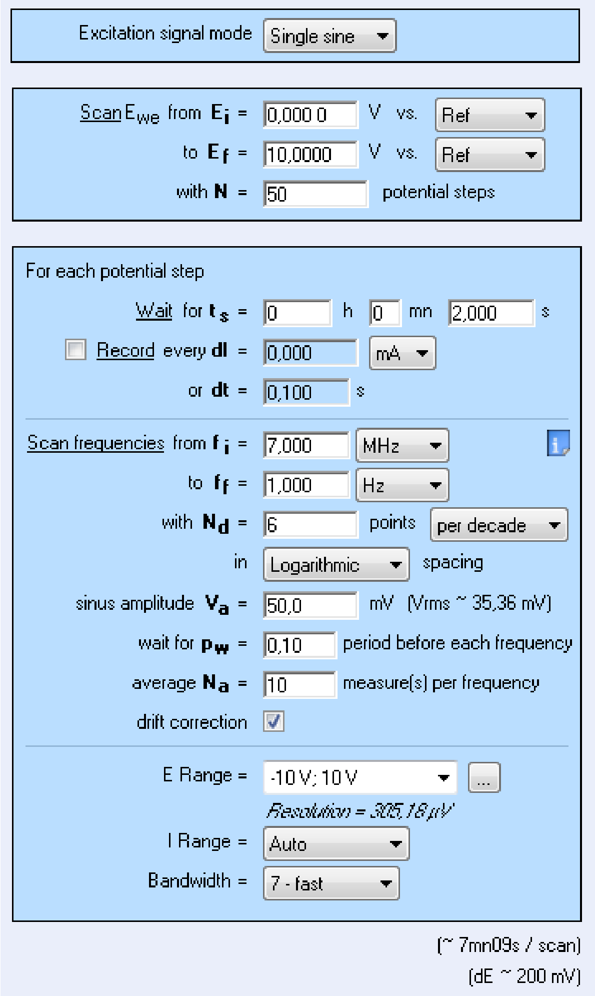


☐ Multi files
Select current cycle
C1/R1
Method Randomize + Simplex
Stop randomize on 5000 iterations
Stop fit on 10000 iterations
Weight |Z|
☐ Save result automatically

param.	sel.	sign	value	unit	dev.
C1	☑	+	0,145 8e-9	F	3,689e-21
R1	☑	+	69,75e9	Ohm	0,349 4
	☐				
	☐				
	☐				
	☐				
	☐				
	☐				
	☐				
	☐				

χ^2 57,1e18
$\chi/\sqrt{N}$ 1,001e9
$\chi^2/|Z|$ 0,020 96
Cycle 1
Iterations 10000 (Simplex)

Figure 4: Values of the Zfit process.



Excitation signal mode: Single sine

Scan Ewe from Ei = 0,000 0 V vs. Ref
to Ef = 10,0000 V vs. Ref
with N = 50 potential steps

For each potential step
Wait for ts = 0 h 0 mn 2,000 s
☐ Record every dI = 0,000 mA
or dt = 0,100 s

Scan frequencies from fi = 7,000 MHz
to ff = 1,000 Hz
with Nd = 6 points per decade
in Logarithmic spacing
sinus amplitude Va = 50,0 mV (Vrms ~ 35,36 mV)
wait for pw = 0,10 period before each frequency
average Na = 10 measure(s) per frequency
drift correction ☑

E Range = -10 V; 10 V
Resolution = 305,18 µV
I Range = Auto
Bandwidth = 7 - fast

(~ 7mn09s / scan)
(dE ~ 200 mV)

Figure 5: SPEIS settings for varia-capacitor characterizations.

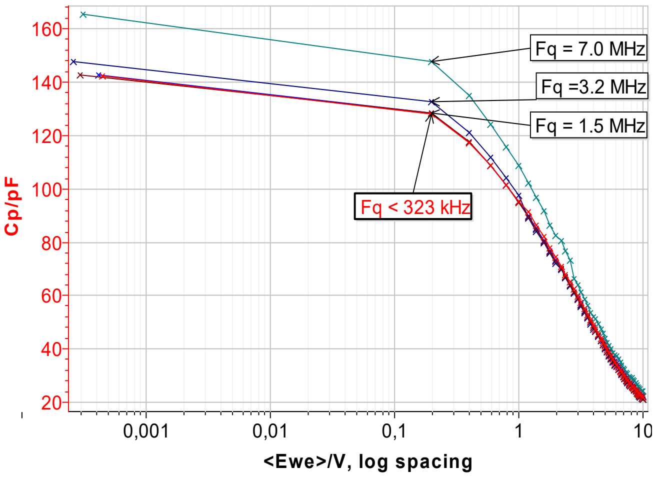
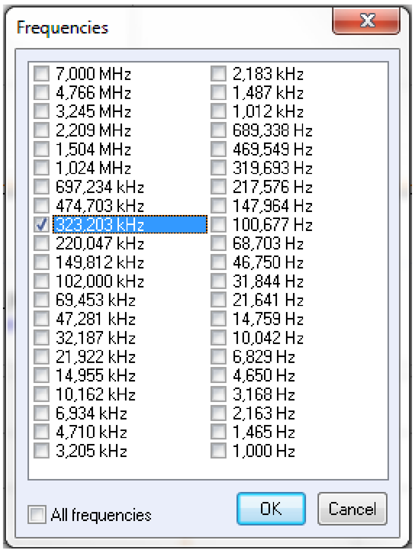


Figure 6: *C-V* characterization at different frequencies.

The SPEIS$_{7MHz-1Hz}$ allows users to fit the capacitance value, C_1 with the Zfit tool at the different frequencies (window of frequency selection is displayed in Fig. 7). C_1 is compared in Fig. 8 to the value of C_p that is already calculated during the experiments SPEIS$_{7MHz-1Hz}$ and SPEIS$_{323kHz}$. C_1 and C_p leads to similar values around 140 pF at low voltage and 20 pF at high voltage. So, the comparison shows that the C_1 calculated with Zfit and C_p determined directly in the EIS technique are identical.

These values are in agreement with the specification described in the datasheet of the varia-capacitor.

Moreover, SPEIS$_{7MHz-1Hz}$ and SPEIS$_{323kHz}$ last 6 200 s and 150 s, respectively. So it is possible to save time by performing SPEIS at one frequency.



☐ 7,000 MHz
☐ 4,766 MHz
☐ 3,245 MHz
☐ 2,209 MHz
☐ 1,504 MHz
☐ 1,024 MHz
☐ 697,234 kHz
☐ 474,703 kHz
☑ 323,203 kHz
☐ 220,047 kHz
☐ 149,812 kHz
☐ 102,000 kHz
☐ 69,453 kHz
☐ 47,281 kHz
☐ 32,187 kHz
☐ 21,922 kHz
☐ 14,955 kHz
☐ 10,162 kHz
☐ 6,934 kHz
☐ 4,710 kHz
☐ 3,205 kHz
☐ 2,183 kHz
☐ 1,487 kHz
☐ 1,012 kHz
☐ 689,338 Hz
☐ 469,549 Hz
☐ 319,693 Hz
☐ 217,576 Hz
☐ 147,964 Hz
☐ 100,677 Hz
☐ 68,703 Hz
☐ 46,750 Hz
☐ 31,844 Hz
☐ 21,641 Hz
☐ 14,759 Hz
☐ 10,042 Hz
☐ 6,829 Hz
☐ 4,650 Hz
☐ 3,168 Hz
☐ 2,163 Hz
☐ 1,465 Hz
☐ 1,000 Hz

☐ All frequencies

Figure 7: Frequency selection.

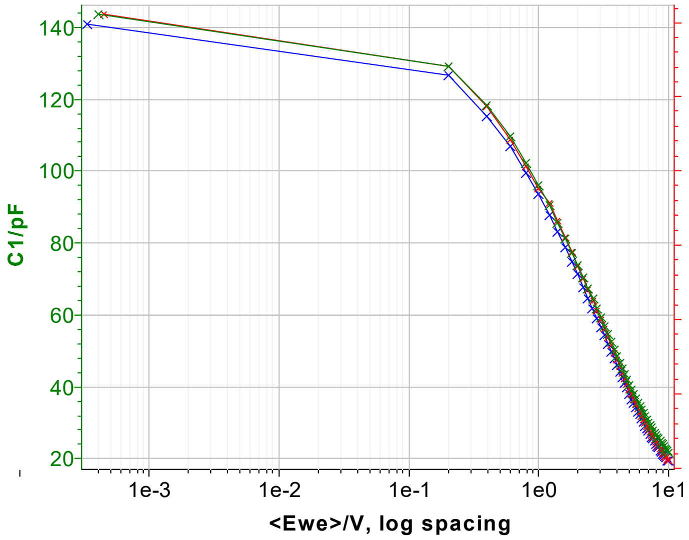


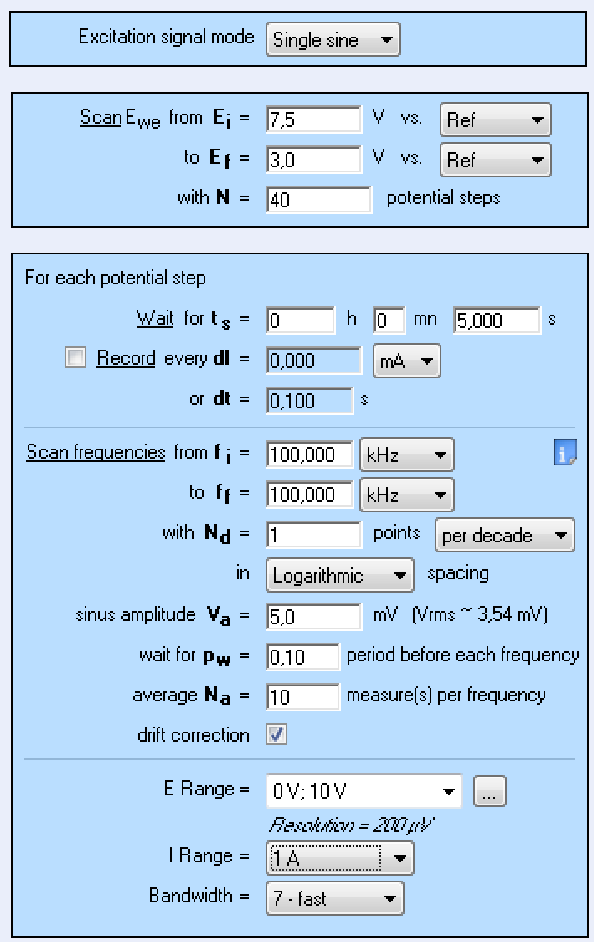
Figure 8: semi logarithmic *C-V* curves of varia capacitor. *C_p vs E* of SPEIS$_{323kHz}$; *C_p vs. E* of SPEIS$_{7MHz-1Hz}$ and C_1 (from Zfit) *vs. E* of SPEIS$_{7MHz-1Hz}$.

IV – *C-V* CURVE OF PHOTOVOLTAIC CELL

For the PV cell characterization, the voltage is scanned between 3 and 7.5 V and the frequency of the signal is 100 kHz (Fig, 9). According to the application note #24 [1], R/C model is considered. So C_p *vs V* curve is plotted (Fig. 10).

The *C-V* curve exhibits 3 regions:

- *E* < 4V: accumulation region
- 4V < *E* <6V: depletion region
- *E* > 6V: Inversion region



Excitation signal mode: Single sine

Scan E_{we} from E_i = 7,5 V vs. Ref
to E_f = 3,0 V vs. Ref
with N = 40 potential steps

For each potential step
Wait for t_s = 0 h 0 mn 5,000 s
☐ Record every dI = 0,000 mA
or dt = 0,100 s
Scan frequencies from f_i = 100,000 kHz
to f_f = 100,000 kHz
with N_d = 1 points per decade
in Logarithmic spacing
sinus amplitude V_a = 5,0 mV (Vrms ~ 3,54 mV)
wait for p_w = 0,10 period before each frequency
average N_a = 10 measure(s) per frequency
drift correction ☑
E Range = 0 V; 10 V
Resolution = 200 µV
I Range = 1 A
Bandwidth = 7 - fast

Figure 9: *C-V* curves settings of PV cell characterization.

The doping concentration N can be determined thanks to the following relationship:

$$N = \frac{2}{e\varepsilon\varepsilon_0 A^2 \left(\frac{d\left(\frac{1}{C^2}\right)}{dE}\right)} \qquad (1)$$

Where *e* is the electron charge (1.60 x 10^{-19} C)
ε_0 is the semiconductor permittivity (1.03 x 10^{-12} F/cm for silicon)
A is the surface of the photovoltaic cell, 21 cm^2
C is the capacitance (F) and *E* the voltage (V).

As C^{-2} variable is also available in the list of available variable (Fig. 1), it is also possible to plot C^{-2} *vs. E*. The slope of this curve leads to the doping concentration.

In this case, the slope (determined by linear fit) is 3.53 x 10^{15} F/V, so the doping concentration is 1.64 x 10^{14} cm^{-3}. This value is in agreement with a value previously given [1].

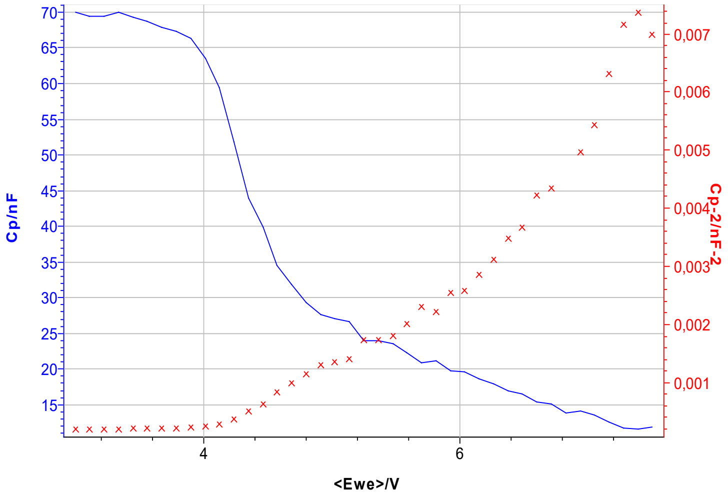


Figure 10: *C-V* curves of photovoltaic cell. C_p *vs. E* and C_p^{-2} *vs. E*.

IV – CONCLUSION

The note shows how to perform capacitance measurements without any fitting process. This offers several advantages:

- Quick measurement, only one frequency is needed to determine C_p or C_s. No need for the full EIS spectra.
- No post-treatment: no impedance fitting process is needed

- The graphic package of EC-Lab allows one to plot different types of graph such as *C vs. E* in log spacing, C^{-2} *vs. E*, and even more…

It is possible to follow up the capacitance change that can be carried out with the PEISW technique. This technique is also of interest for sensor applications.

Data files can be found in :
C:\Users\xxx\Documents\EC-Lab\Data\Samples\Photovoltaic\X_C_V_Charact

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REFERENCES

1) Application Note #24 “Photovoltaic Characterizations: Polarization and Mott-Schottky plot”

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