Bias dependent admittance spectroscopy of thin film solar cells: Simulations

Guy Brammertz, Thierry Kohl, Jessica de Wild, Dilara Gokcen Buldu, Gizem Birant, Marc Meuris, Jozef Poortmans, and Bart Vermang

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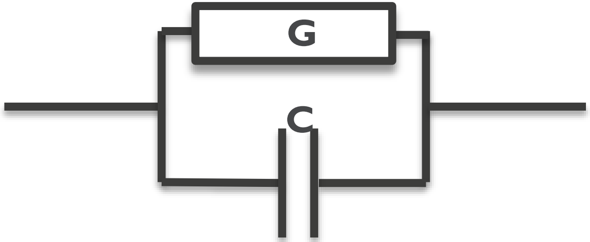
Admittance spectroscopy: Experimental setup

- CIGS solar cell sample (Mo/co-evap CIGS/CdS/i-ZnO/AZO)
- LCR-meter with DC-bias option (Agilent E4980A)
- Needle probes (4-point or 2-point)

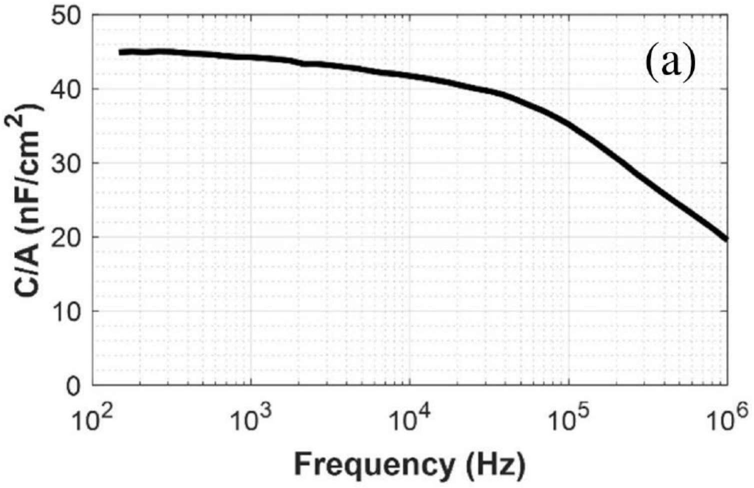
- Measurement of the parallel capacitance and conductance at room temperature with:
  - 50 different frequencies varying logarithmically from 100 Hz to 1 MHz
  - 51 different bias voltages varying from -1.5 V to 1 V



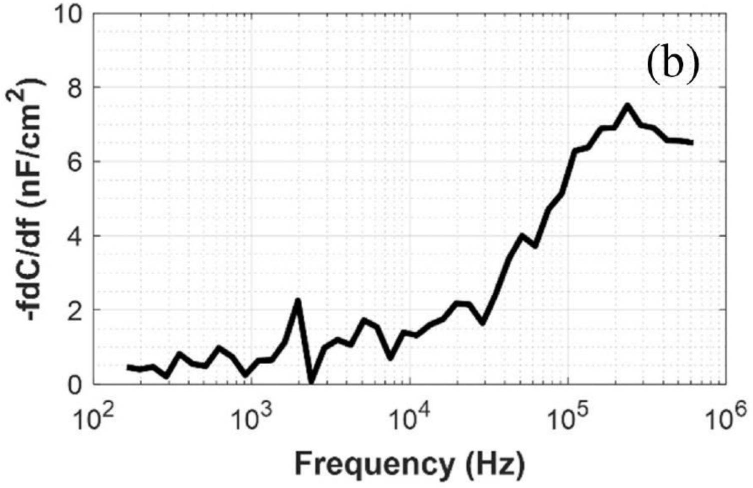
→ 50 x 51 (2550) measurement values for C and G

Measurement results

C versus f at 0 V

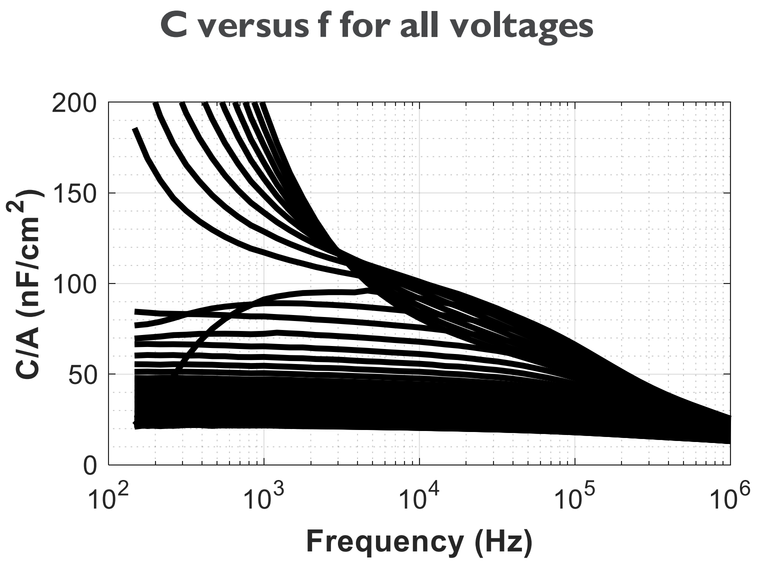


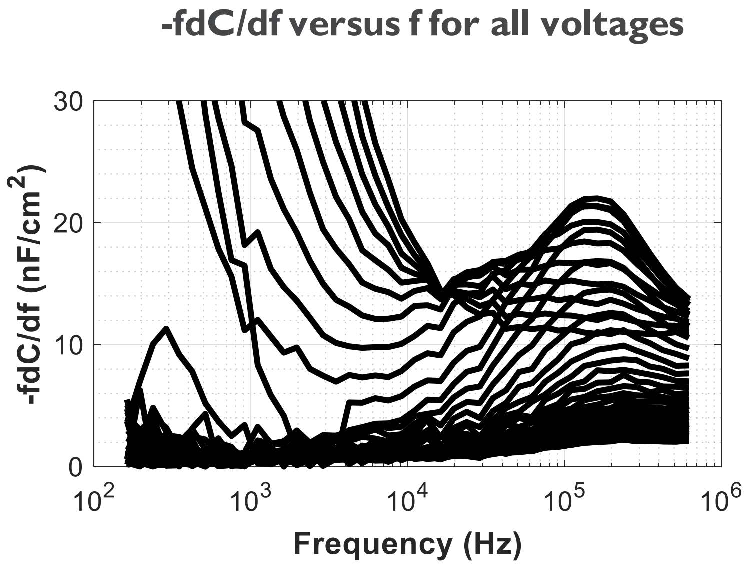
-fdC/df versus f at 0 V



- Only room temperature data shown here.
- In general, measurements at different temperatures shown as well, in order to make an Arrhenius plot and to extract the activation energy → not the focus here.
- We will investigate here what we can do with the data from the other 50 bias voltages.

Measurement results

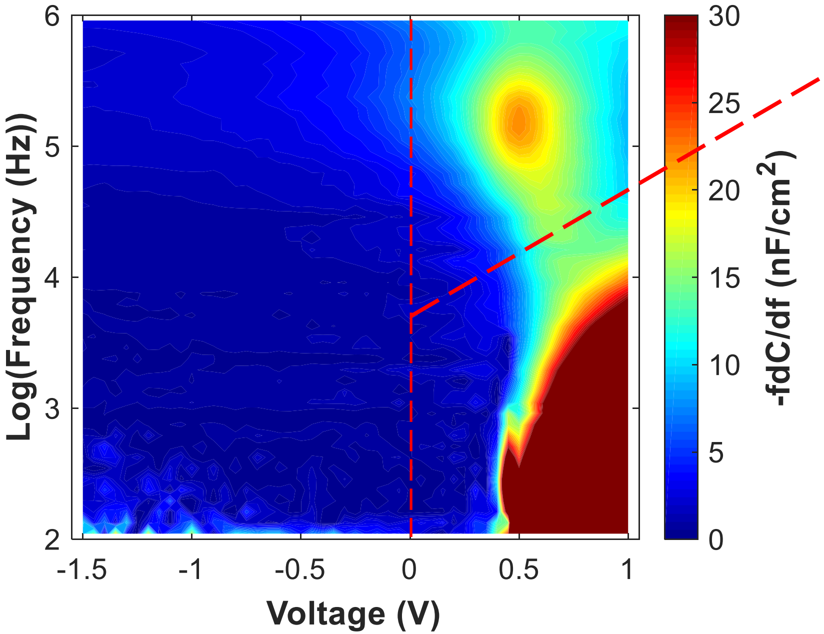


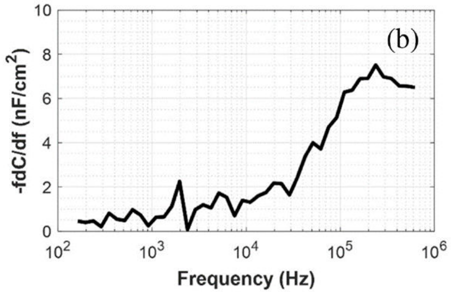


- Only room temperature data shown here.
- Possible, but quite messy data, difficult to get valid information from this type of graph.

CVf - loss map[1]

2 D map of -fdC/df versus log(f) and voltage





- Better graphical representation of the data.
- Continuous response domains can be identified.
- Every response in this map corresponds to a charge loss event, basically a resistive response, therefore the name "CVf ***loss map***".

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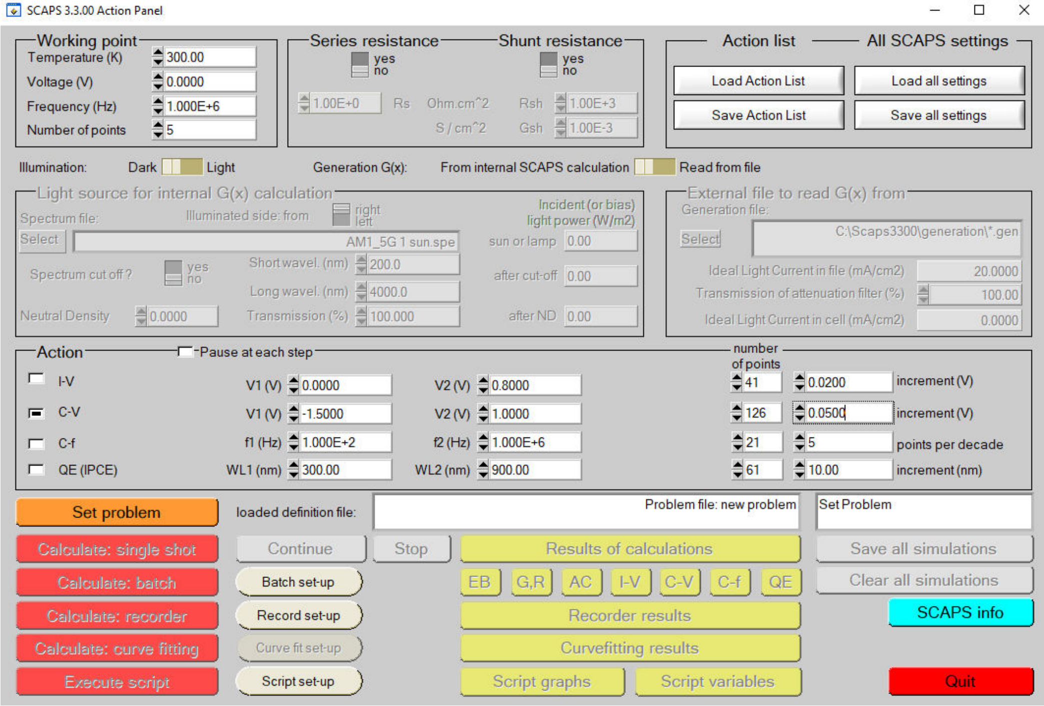
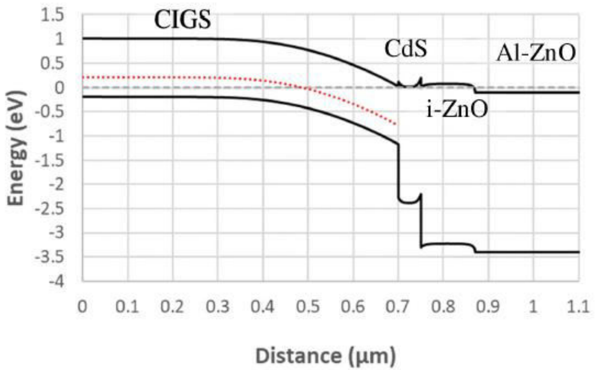
[1] G. Brammertz et al, accepted in IEEE JPV (2020) - DOI: 10.1109/JPHOTOV.2020.2992350

Loss map simulations: SCAPS[1]

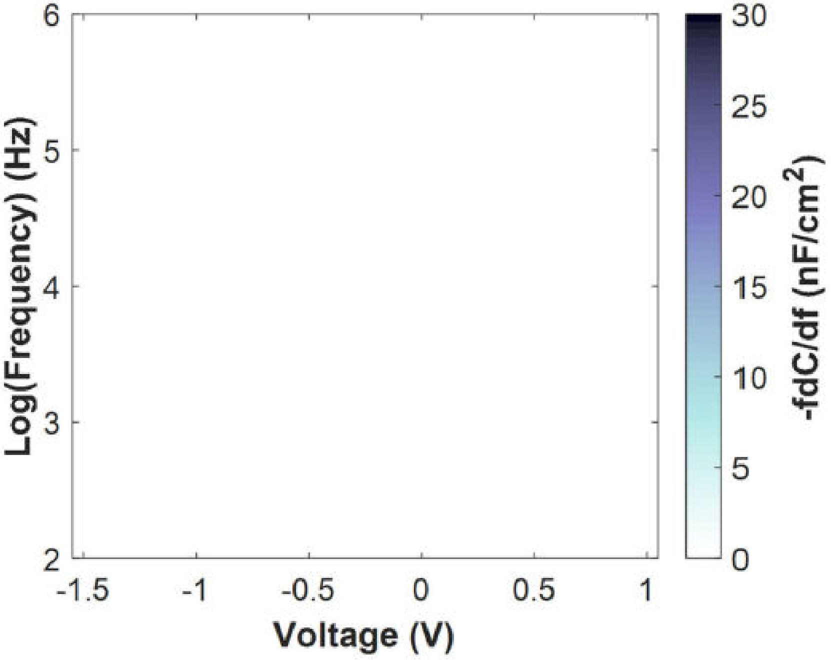




- Simulation of Capacitance of CIGS solar cell structure as a function of bias voltage and as a function of frequency.

[1] M. Burgelman et al., Prog. Photovolt: Res. Appl. 11, 1-11 (2003)

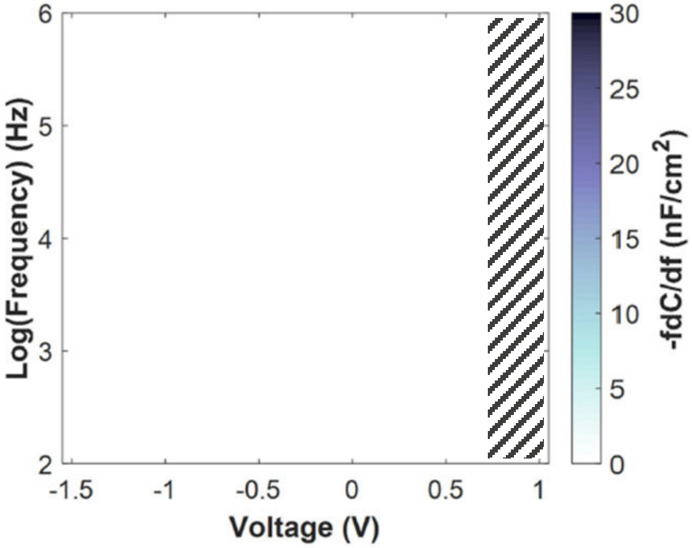
Loss map simulations: No defects

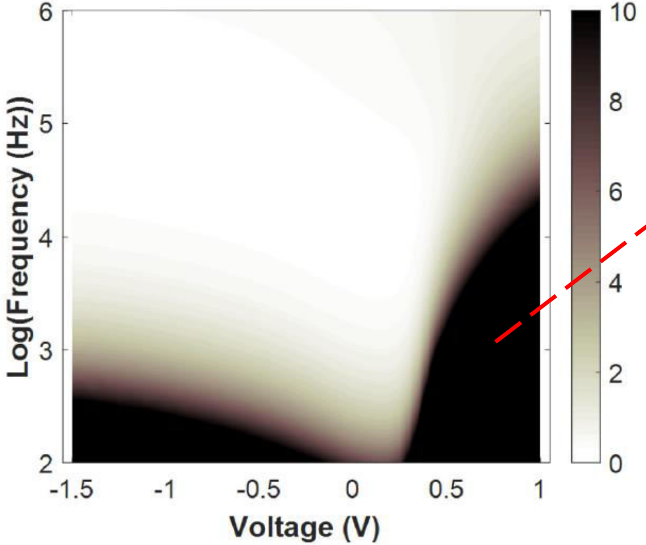


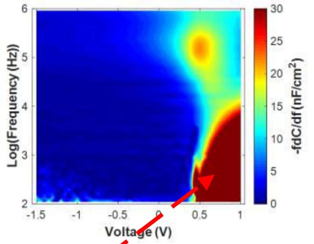
- No defects in the solar cell structure lead to an empty loss map, as there are no losses involved.

[1] G. Brammertz et al, accepted in IEEE JPV (2020) - DOI: 10.1109/JPHOTOV.2020.2992350

Loss map simulations: shunt resistance







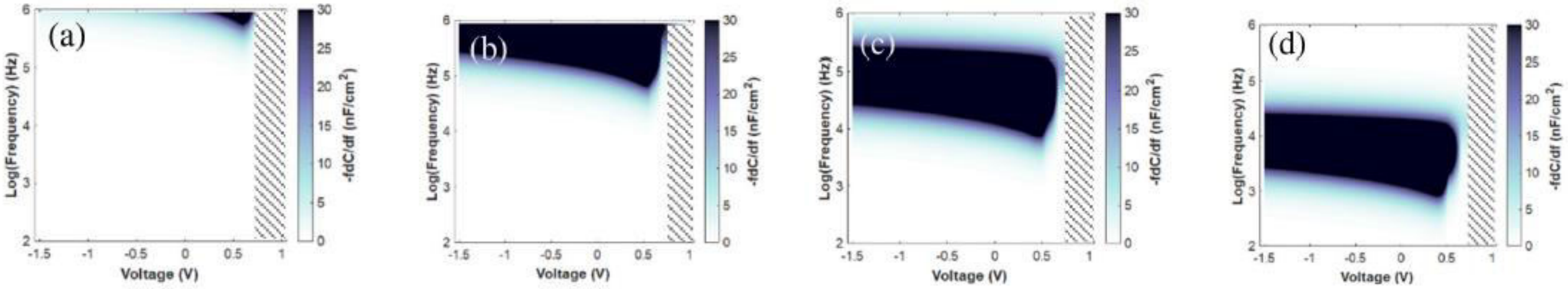
$$D = \frac{G_p}{2\pi f C_p}$$

- The shunt resistance has no direct influence on the loss map.
- It does influence the dissipation factor though.
- If dissipation factor is too large, the tool cannot measure the capacitance accurately anymore.

[1] G. Brammertz et al, accepted in IEEE JPV (2020) - DOI: 10.1109/JPHOTOV.2020.2992350

Loss map simulations: series resistance

R_s = 1 Ω cm² | R_s = 10 Ω cm² | R_s = 100 Ω cm² | R_s = 1000 Ω cm²



- Series resistance leads to an almost horizontal response in the loss map.
- Response frequency can be calculated with cut-off frequency of RC-circuit: $f_c^{-1} = 2\pi RC$.
- For typical series resistance values of solar cell devices only small response at frequencies around 1 MHz is visible.

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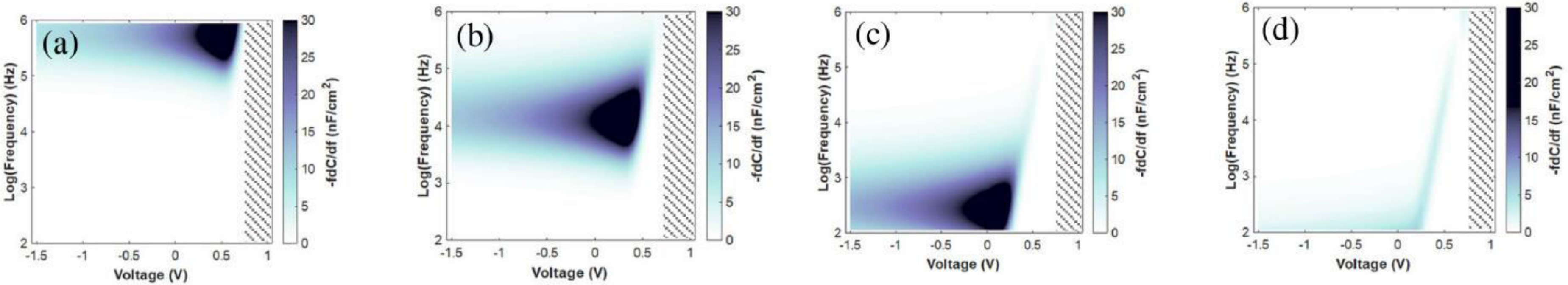
Loss map simulations: bulk defects in the CIGS

- 10^{16} cm^{-3} acceptor-like defects above the valence band edge energy of the CIGS.
- Capture cross-section of 10^{-15} cm^{-2} assumed.

E_a = 0.3 eV | E_a = 0.4 eV | E_a = 0.5 eV | E_a = 0.6 eV



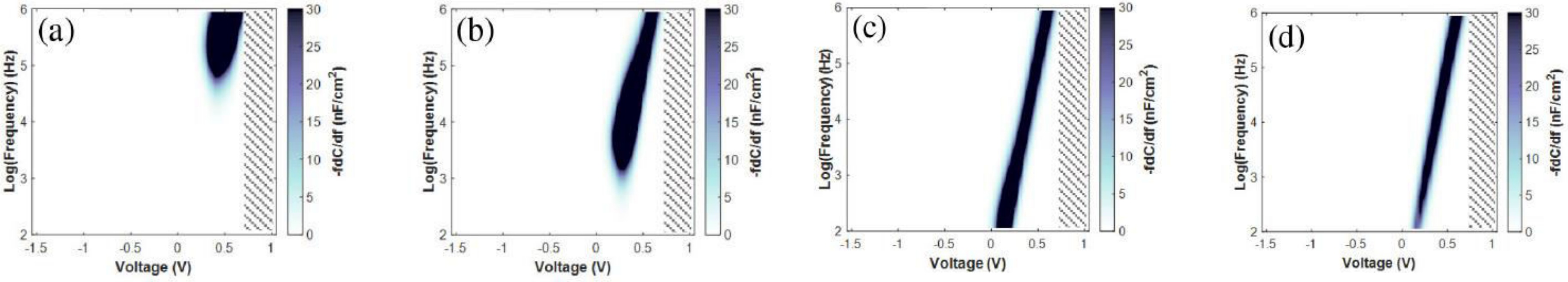
- Broad response over the full bias range.
- The intensity of the response with respect to bias voltage follows the depletion layer capacitance.
- Exact determination of the activation energy needs temperature dependent-measurements.

[1] G. Brammertz et al, accepted in IEEE JPV (2020) - DOI: 10.1109/JPHOTOV.2020.2992350

Loss map simulations: defects at the CIGS/CdS interface

- 10^{12} cm^{-2} eV^{-1} acceptor-like defects above the valence band edge energy of the CIGS.
- Capture cross-section of 10^{-15} cm^{-2} assumed.

E_a = 0.3 eV | E_a = 0.4 eV | E_a = 0.5 eV | E_a = 0.6 eV



- Quite localized response over small bias range.
- Quite complex behavior:
  - If density too large → Fermi level pinning (bias independent response)
  - Depends strongly on doping in CdS (can vary the Fermi level position at the interface)

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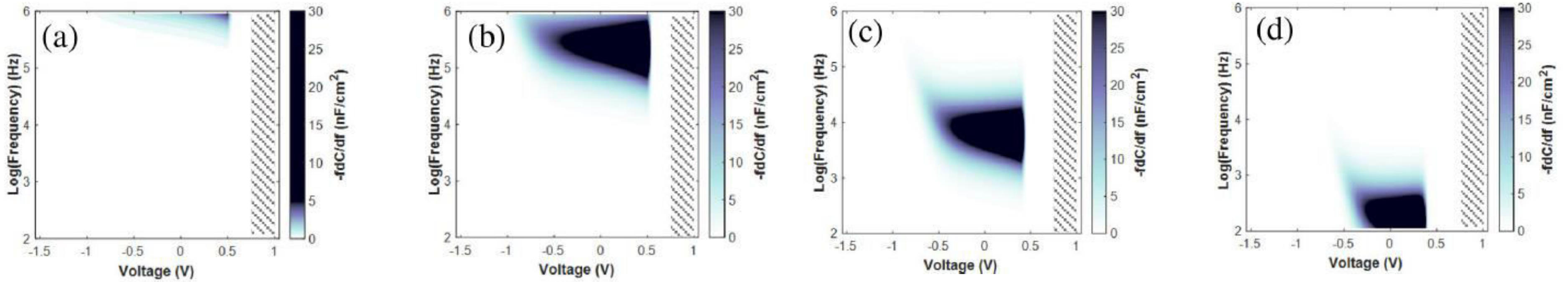
Loss map simulations: barrier at the back contact

- Backside barrier with varying barrier height.

E_a = 0.2 eV E_a = 0.3 eV E_a = 0.4 eV E_a = 0.5 eV

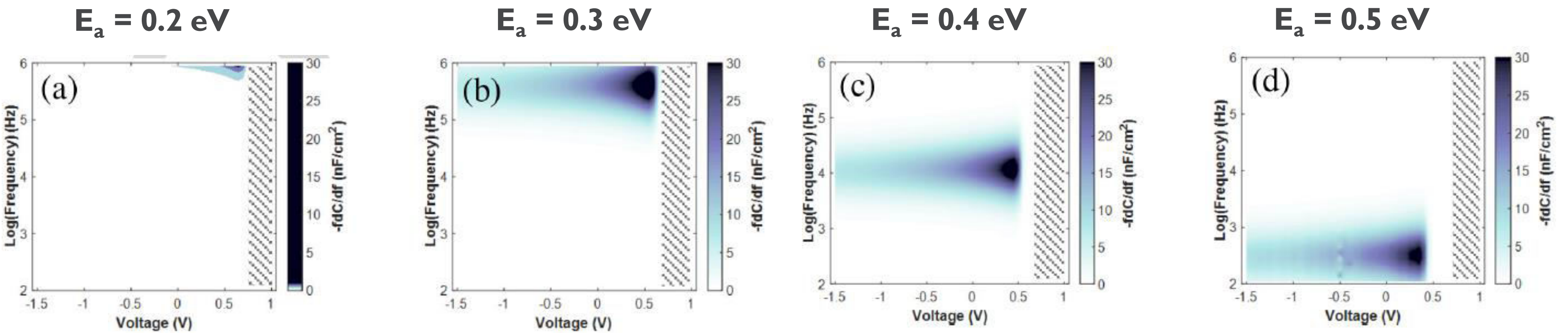


- Decrease in response frequency as barrier height increases.
- Slight upward tail.

[1] G. Brammertz et al, accepted in IEEE JPV (2020) - DOI: 10.1109/JPHOTOV.2020.2992350

Loss map simulations: barrier at the CIGS/CdS interface

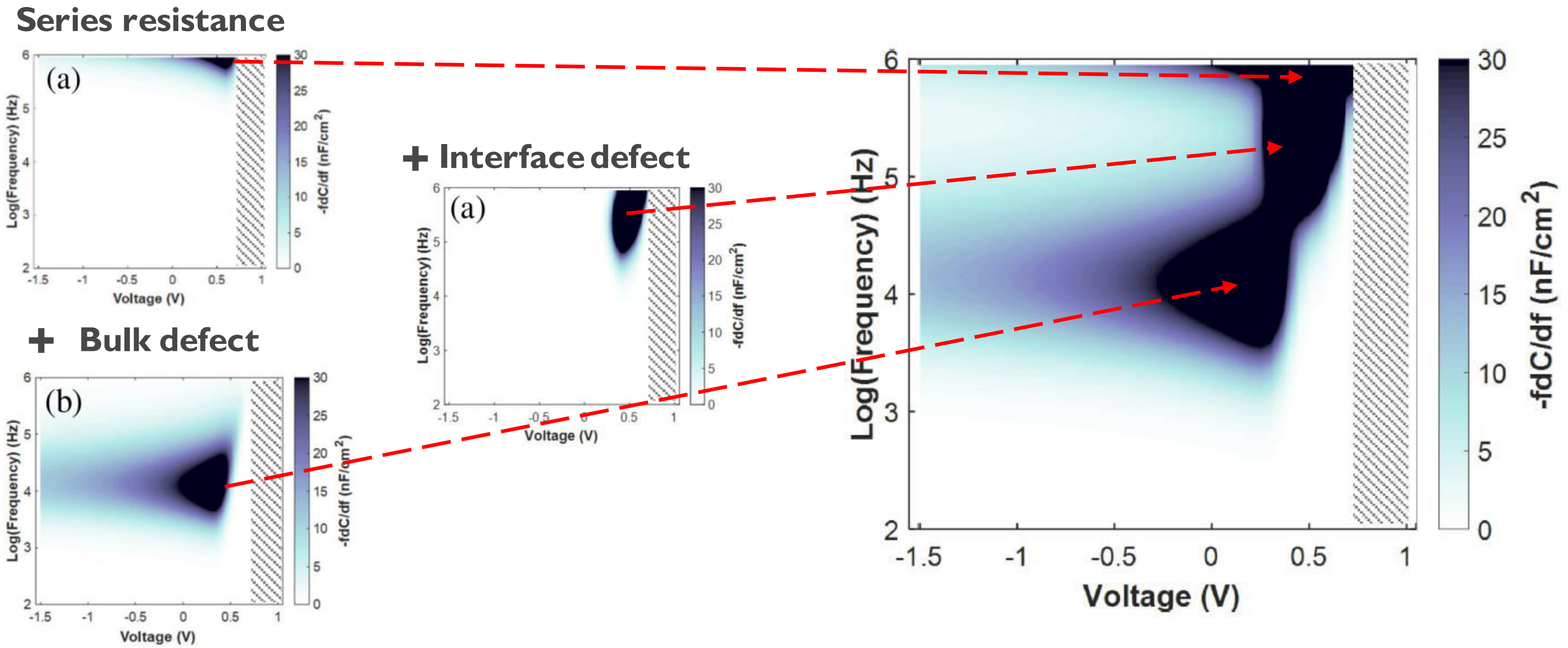
- Spike-like barrier at the CIGS-CdS interface with varying barrier height.



- Decrease in response frequency as barrier height increases.
- Response frequency totally independent of bias voltage.

[1] G. Brammertz et al, accepted in IEEE JPV (2020) - DOI: 10.1109/JPHOTOV.2020.2992350

Loss map simulations: Different defects simultaneously



- Adding different defects in the solar cell structure at the same time, leads to a loss map where all the responses from the different defects add up.
- This is no longer true if one of the defects creates Fermi-level pinning, as that inhibits the movement of the Fermi level, possibly hiding some defect responses that otherwise would have been present.

[1] G. Brammertz et al, accepted in IEEE JPV (2020) - DOI: 10.1109/JPHOTOV.2020.2992350

Conclusions

- We have introduced a "CVf loss map", which plots -fdC/df as a function of bias voltage and frequency.
- We have then made SCAPS simulations in order to simulate the loss map for different typical defects that can be present in a solar cell structure.
- Even though quite complex, these loss maps might be helpful for finding possible root causes for defect responses in solar cells.

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