The modulated photoluminescence technique as a support to improve the quality of solar cell absorbers.

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During the last years, we developed an efficient High-Frequency Modulated Photoluminescence (MPL) setup at IPVF, covering a frequency range of 500Hz-200MHz. This is one of only two setups in the world able to probe such a wide dynamic range [1],[2]. As previously described, V-shaped phase patterns in the MPL curves were observed at low illumination fluxes, which were assigned to the presence of traps [3] [4], in accordance with analytical calculations developed by N. Moron [4] using Shockley-Read-Hall formalism. This setup has been used for one year to probe thin-films of several solar cell absorber materials, including halide perovskite and CIGS in the frame of several collaborations and projects (IPVF programmes, ANR MOPGA, ANR PASTEL). Several illustrations will be given. One of the most recent interesting results is a correlation between the defect density observed by MPL and the CIGS efficiency (figure 1). The exact nature of the observed defect is presently investigated by admittance spectroscopy, Fourier Transform Photocurrent Spectroscopy (FTPS) and temperature-dependent MPL experiments. In the case of perovskites, we observed a rich variety of defects depending on the film composition, fabrication parameters, and surface treatment.

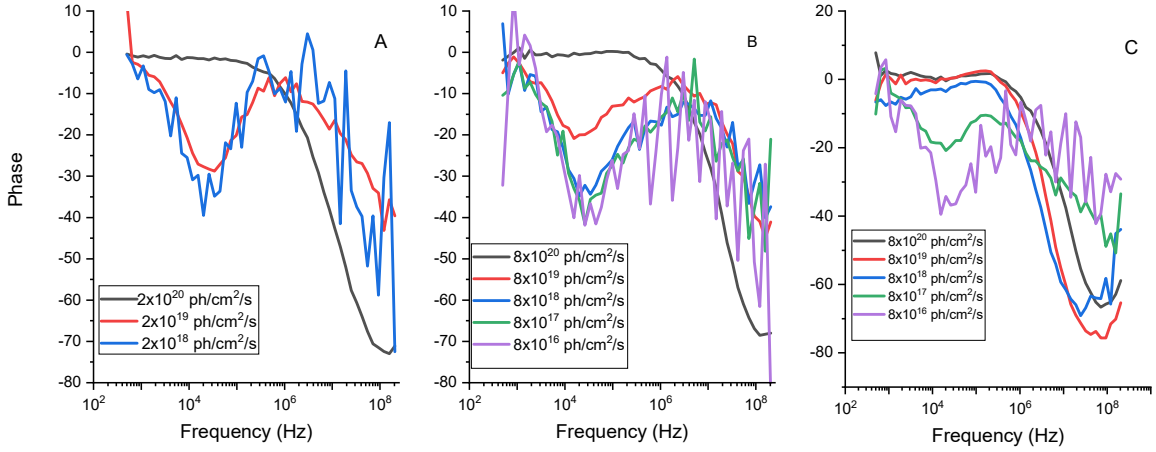

Figure. A: MPL signature of the CIGS baseline material fabricated at IPVF for three different samples presenting efficiencies ranging from A) 12% B) 15% C) 19%. Measurements become noisier and the MPL amplitude decreases (not shown here) when decreasing the excitation intensity. The fact that we can measure a reliable PL signal with 25 times lower excitation on sample C in comparison to sample A and the disappearance of the V-shape at lower illumination for C is a proof that the observed defect is directly linked to the efficiency of the cell.

[1] I. Reklaitis *et al.*, « Photoluminescence Decay Dynamics in Blue and Green InGaN LED Structures Revealed by the Frequency-Domain Technique », *J. Electron. Mater.*, vol. 45, nº 7, p. 3290-3299, juill. 2016, doi: 10.1007/s11664-016-4557-7.

[2] W. Zhao *et al.*, « Coupled time resolved and high frequency modulated photoluminescence probing surface passivation of highly doped n-type InP samples », *J. Appl. Phys.*, vol. 129, nº 21, p. 215305, juin 2021, doi: 10.1063/5.0033122.

[3] B. Bérenguier *et al.*, « Defects characterization in thin films photovoltaics materials by correlated high-frequency modulated and time resolved photoluminescence: An application to Cu(In,Ga)Se2 », *Thin Solid Films*, vol. 669, p. 520-524, janv. 2019, doi: 10.1016/j.tsf.2018.11.030.

[4] N. Moron, B. Bérenguier, J. Alvarez, et J.-P. Kleider, « Analytical model of the modulated photoluminescence in semiconductor materials », *J. Phys. Appl. Phys.*, vol. 55, nº 10, p. 105103, mars 2022, doi: 10.1088/1361-6463/ac39c4.