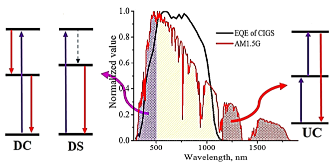
Piotr Zabierowski[1,2,3], Anatolie Gavriluta[2], Charlène Crevant[5], Aline Nonat[3], Loïc J. Charbonnière[3], Thomas Fix[2], Philippe Baranek[5], Frédérique Donsanti[5], Anne-Laure Joudrier[1,4], Laurent Lombez[5] and Jean-François Guillemoles[5]

1) Institut Photovoltaïque d'Ile-de-France 18, boulevard Thomas Gobert, 91120 Palaiseau, FRANCE
2) ICube Laboratory , Université de Strasbourg and CNRS, 23 rue du Loess BP 20 CR, 67037 Strasbourg Cedex 2, FRANCE
3) SynPA, IPHC, UMR 7178 CNRS, Université de Strasbourg, ECPM, 25 rue Becquerel, 67087 Strasbourg Cedex, FRANCE
4) Chimie ParisTech, École Nationale Supérieure de Chimie de Paris, 11 rue Pierre et Marie Curie, 75231 PARIS cedex 05, FRANCE
5) UMR IPVF: CNRS, Ecole Polytechnique, Chimie Paristech, EDF, TOTAL, Airliquide, Institut Photovoltaïque d'Ile-de-France 18, boulevard Thomas Gobert, 91120 Palaiseau, FRANCE

IUPAC PARIS - FRANCE JULY 5-12 2019

Luminescent down-shifters and down-converters for third generation solar cells

Spectral modification for 3rd generation solar cells [1]



The solar spectrum AM1.5G (red line) compared to the absorption spectrum of silicon (black line). The UV photons can be efficiently shifted into region of maximum absorbance by downconversion (DC) or downshifting (DS) while the NIR photons by upconversion (UC); shown on the scheme.

3rd GENERATION SOLAR CELLS
Solar cells overcoming the Shockley Queisser limit

Different technologies are developed:
- Concentrator solar cells
- Multijunctions
- Hot carriers
- frequency conversion: DC/DS, UC

DS/DC and UC realisation:
- inclusion of fluorophores in a matrix
- encapsulation of fluorophores in top/middle/bottom layers
- fluorophores: organic dyes, lanthanide compounds, quantum dots, nanoparticles

Analytical model in description of LDS layers – figures of merit [2]

$$\mathrm{PLQY} = \frac{\int \mathrm{Em}(\lambda)d\lambda}{\int \mathrm{A}(\lambda)\theta(\lambda)d\lambda}$$

$$\mathrm{ASM} = \frac{\int (1-\mathrm{T}(\lambda))(1-\mathrm{EQE}(\lambda))\psi(\lambda)d\lambda}{\int_{300\ \mathrm{nm}}^{405\ \mathrm{nm}} (1-\mathrm{EQE}(\lambda))\psi(\lambda)d\lambda}$$

$$\mathrm{RO} = \frac{\int \mathrm{Em}(\lambda)(1-\mathrm{T}(\lambda))d\lambda}{\int \mathrm{Em}(\lambda)d\lambda}$$

$$\mathrm{ESM} = \frac{\int \mathrm{Em}(\lambda)\mathrm{EQE}(\lambda)d\lambda}{\int Em(\lambda)d\lambda}$$

$$\mathrm{PA} = \frac{\int_{410\ \mathrm{nm}}^{1200\ \mathrm{nm}} (1-\mathrm{T}(\lambda))\mathrm{EQE}(\lambda)\psi(\lambda)d\lambda}{\int_{410\ \mathrm{nm}}^{1200\ \mathrm{nm}} \mathrm{EQE}(\lambda)\psi(\lambda)d\lambda}$$

$$\Delta \mathrm{J_{SC}} = \mathrm{ESM}\ Q(1-\bar{R}c)(\mathrm{ASM}\ \Delta \mathrm{J_{SC^{max}}} - \mathrm{PA}) - \mathrm{PA}$$

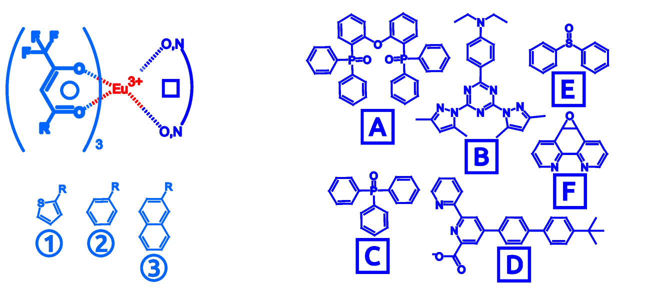
$$Q = \frac{(1-r_{oc})(1-P)\mathrm{PLQY}}{1-\mathrm{PLQY}[r_{ic}P + (1-P)r_{oc}]}$$

$$P = \frac{1}{2}\left[1-\sqrt{1-\frac{1}{n^2}}\right]$$

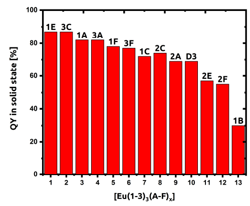
$$\Delta J_{SC^{max}} = \frac{\int_{300\ nm}^{405\ nm} (1-\mathrm{EQE}(\lambda))\psi(\lambda)d\lambda}{\int \mathrm{EQE}(\lambda)\psi(\lambda)d\lambda}$$

Legend: **EQE** – external quantum efficiency; **PLQY** – photoluminescence quantum yield; **ASM** – absorption spectral matching; **RO** – radiative overlap; **ESM** – emission spectral matching; **PA** – parasitic absorption; **J_{sc}** – short circuit current; **Rc** – average reflection at the air cover interface; **Q** – collection probability; **P** – probablility of the downshifted photon emitted within the escape cone; **r** – probability of the downshifted photon being reabsorbed by another dye molecule; **n** – refractive index of the medium.

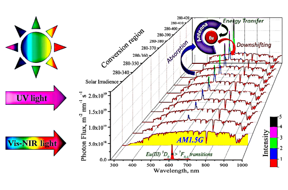
Luminescent Eu(III) downshifters [3, 4, 5]



The chemical structure of the ligands and complexes of Eu^{3+} used to produce the LDS layers.[3, 4, 5] Rectangles denote the type of co-ligand and circle denotes the *R* substitution in *tris*-ligand of the complex in reference to QY plot below.

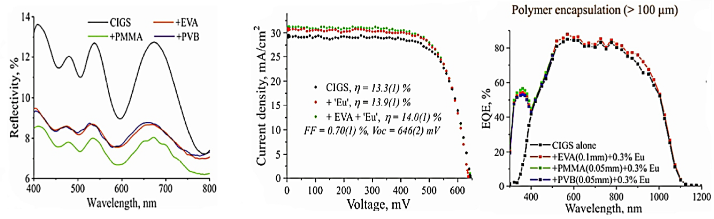


The QY of the complexes of Eu^{3+}, measured in solid state at room temperature. The labels (circle+rectangle) represent combination of ligands in the Eu^{3+} complexes depicted above.



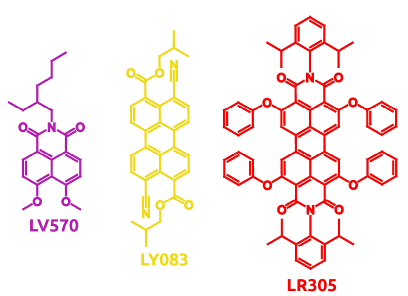
Representation of down-shifting effect of the LDS layers based on Eu^{3+} complexes presented in this communication

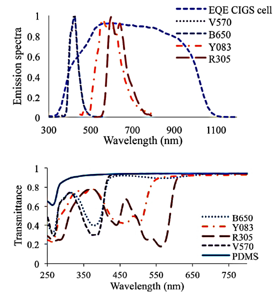
Luminescent Eu(III) LDS Layers [5]



The reflectance spectra as well *I-V* curves registered for the cells with LDS layer composed of Eu(III) luminescent complex with the highest QY. EQE plots for the CIGS without and with LDS layers encapsulated in different types of polymers.

Lumogen dyes in LDS Layers [6, 7]

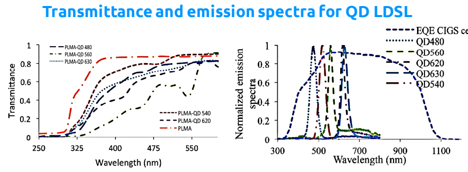


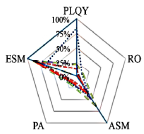


The chemical structures of lumogen family compounds incorporated into PMDS polymer matrix, together with emission and transmittance spectra of the LDS thin films at room temperature.

CdSe/ZnS Quantum Dots in LDSL [6, 7]

Transmittance and emission spectra for QD LDSL

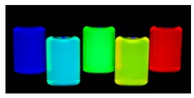




Radar graph comparing the figures of merit[2] for the studied LDSL

The QY of emission of acetone solutions of studied QDs at room temperature.

Dyes materials	Name	Abs. max (nm)	Em. max (nm)	PLQY (%)
QD CdSe/ZnS 480	QD480	-	472	84
QD CdSe/ZnS 540	QD540	-	518	13
QD CdSe/ZnS 560	QD560	-	558	21
QD CdSe/ZnS 620	QD620	-	616	21
QD CdSe/ZnS 630	QD630	-	626	0



The photograph of emission of solutions of CdSe/ZnS QDs in acetone upon UV excitation at room temperature.

Conclusions

- The cascades of lumogen dyes are considered to improove RO and ASM figures of merit of the lumogen single-dye LDSL [6, 7]
- Among studied LSDL the most promising results with CIGS were found for Eu(III) luminescent down-shifters [3, 4, 5]
- The overall gain in efficiency of the CIGS solar cells with europium down-shifters reached 0.8% [5]
- Further work on development of supramolecular down-converting layers is ongoing

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