How to Understand Spectral Photoluminescence from Thin Film Absorbers, Absorber Layer Sequences and Complete Solar Cells

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The spectral photon flux Γ(ω) from a volume element of matter in steady state conditions can be formulated with Planck's generalized law:

$$\Gamma(\omega) = C\mathrm{E}(\omega)\omega^2\left[\exp[\frac{\hbar\omega-\mu_{phot}}{kT}]-1\right]^{-1}, C=\frac{2\Omega}{h^3c^2}$$

, where Ω, h, c, E(ω) and μ_{phot} represent solid angle, Planck's constant, speed of light, spectral emissivity and chemical potential of the photon field.

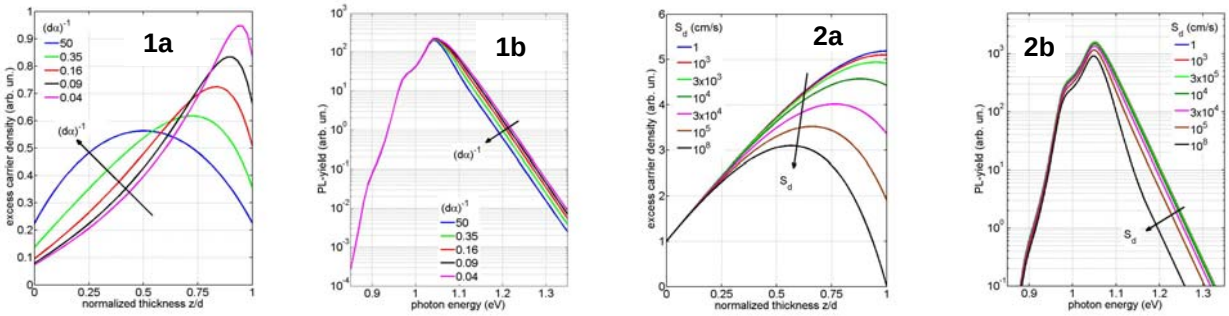
Provided energy and wave vector relaxation times in the excited states are small compared to recombination life times the chemical potential of the photon field μ_{phot} equals the splitting of the quasi-Fermi levels: $\mu_{poht} = \mu_{n,p} = (E_{Fn}-E_{Fp})$ [1,2].

The spectral signal at the detector $\Gamma_{Det}(\omega)$ is composed of each of the contributions of the involved volume elements, which emitting photons into the solid angle 4π that propagate forth and back in the particular layer sequence. This propagation has been formulated with an appropriate matrix transfer formalism taking into account, of course, multi-reflection at phase boundaries with refractive index contrasts, as well as re-absorption of emitted photons in respective layers with non-negligible imaginary part of the refractive indices:

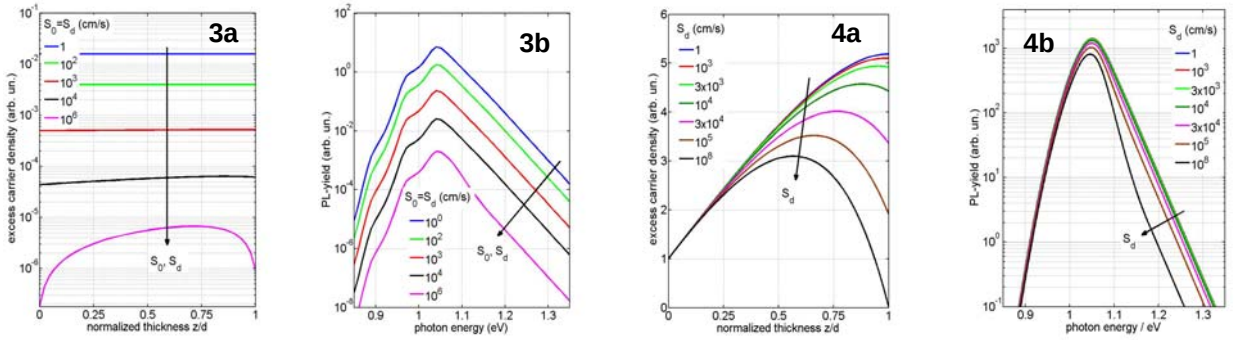
$$\Gamma_{Det}(\omega,z) \propto \Phi_B\left\{(t_{12})^2\exp(-2\alpha(d-z))\left|\frac{1+2r_{10}\exp(-2\alpha z)\exp[i2kz]+(r_{10})^2\exp(-4\alpha z)}{1-2r_{01}r_{12}\exp(-2\alpha d)\exp[i2kd]+(r_{01}r_{12})^2\exp(-4\alpha d)}\right|^2\right.$$

with $\Phi_B = \varepsilon(\omega)\frac{1}{4}\Gamma_{phot}(z)\omega^2\left[\exp[\frac{\hbar\omega-\mu_{n,p}}{kT}]-1\right]^{-1}$.

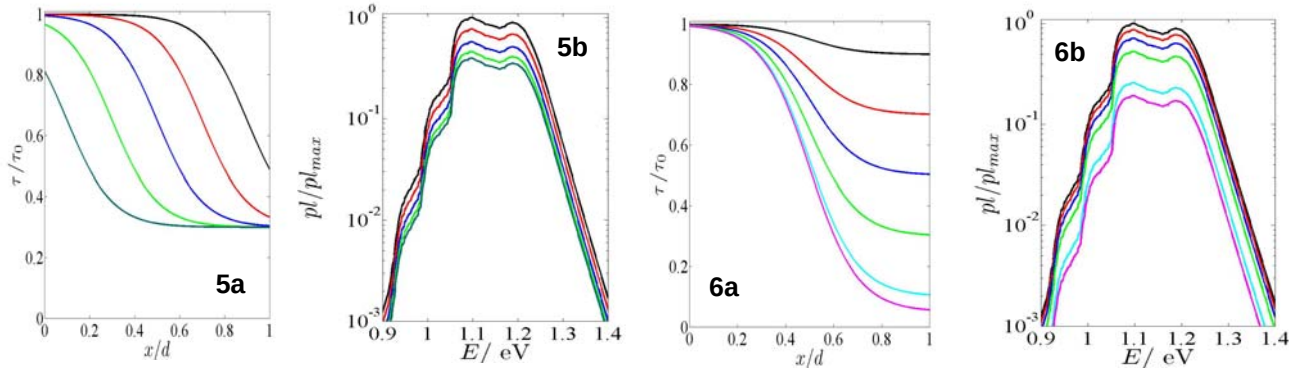
The luminescence flux towards the detector $\Gamma_{Det}(\omega)$ generated in the individual volume elements depends on the photo generated steady state excess carrier contribution which is established according to absorption profiles of excitation light source and their spatial redistribution that can be analytically treated via the stationary continuity equation. The luminescence signal at the detector, in particular the spectral interference behavior strongly depends on the depth position of the luminous centers, say on the depth profiles of the excess carrier density (see figs 1a, 2a for different excess carrier depth profiles and respective spectral luminescence yields, calculated in a 1D-approach (matrix-transfer-formalism) for plane waves propagating forth and back in the absorber of 2mm thickness).



Figs. 1a,b and 2a,b: *Calculated depth profiles of excess carrier densities for varying absorption coefficients α (1a) and surface recombination velocities (S_0, S_d) (2a), and respective spectral luminescence yields (1b, 2b).*



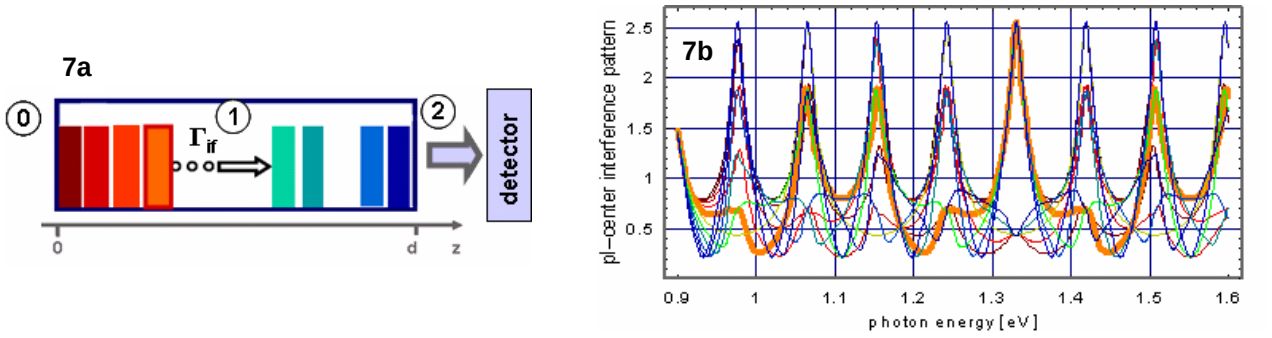
Figs. 3a, b and 4a, b: *Calculated depth profiles of excess carrier densities for different surface recombination velocities (S_0, S_d) (1a, 2a), and respective spectral luminescence yields in 1D plane wave (2a) as well as in a 3D spherical wave approach (4b) (relevant for high local resolution e.g. in SNOM- analyses) which has to be compared to fig. 2b for identical excess carrier profiles (2a) and a 1D-plane wave calculation.*



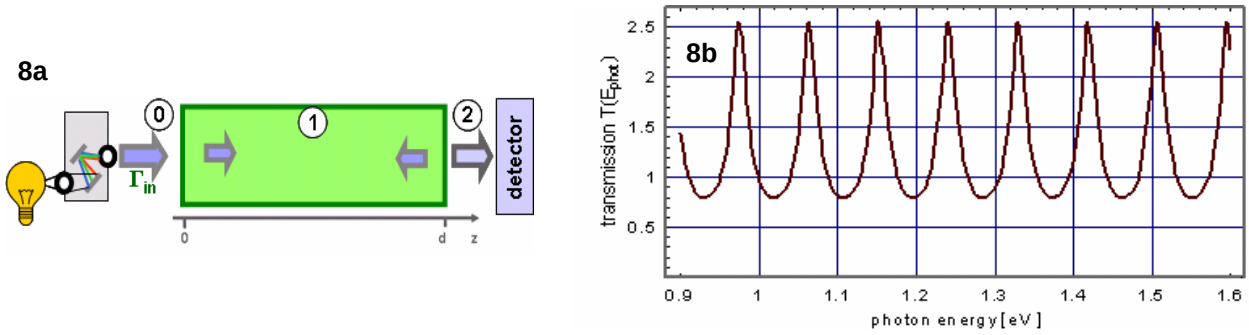
Figs. 5a, b and 6a, b: *artificial variation of depth dependent excess carrier life times (5a, 6a)resulting from front side degradation (e.g. CIS) and according spectral luminescence yields (calculated in 1D plane wave approach) (5b, 6b).*

From the results in figures 1b, 2b, 3b, 4b, 5b, 6b as well as via the analytical formulation of the spectral luminescence yield, we may easily deduce the strong influence of the depth position ξ_i of the centers emitting luminescence photons (local excess carrier density) on the wave-length or energy position of the interference peaks. For the internally generated luminescence the difference in path lengths backward and forward propagating photons (ξ_i+d versus d-ξ_i) at the light outlet side (z=d) decides on the interference behavior.

For the same absorber the interference pattern for spectral transmission/reflection results solely from photon modes propagating across the entire layer thickness d with path length differences 2nd (n=1,2,..). Consequently by comparison of spectral interference patterns in PL and in transmission we may by principle conclude on internal excess carrier depth profiles (see figures 7a,b for interference effects in luminescence and 8a, b for those in transmission).



Figs 7a, b: *Schematic positions of individual luminescent centers across the absorber depth (a) and aaccording spectral luminescence behavior (spectral emissivity and re-absorption are not included in these pattern).*



Figs 8a, b: *Schematic wave propagation in transmission across the absorber depth (a) and according spectral transmission interference pattern (spectral absorption is not included in this pattern).*

[1] P. Würfel, Physics of Solar Cells, Wiley-VCH, Weinheim, 2005.
[2] K. Schick, E. Daub, S. Finkbeiner, P. Würfel, Appl. Phys. Lett A 54 (1992)109.