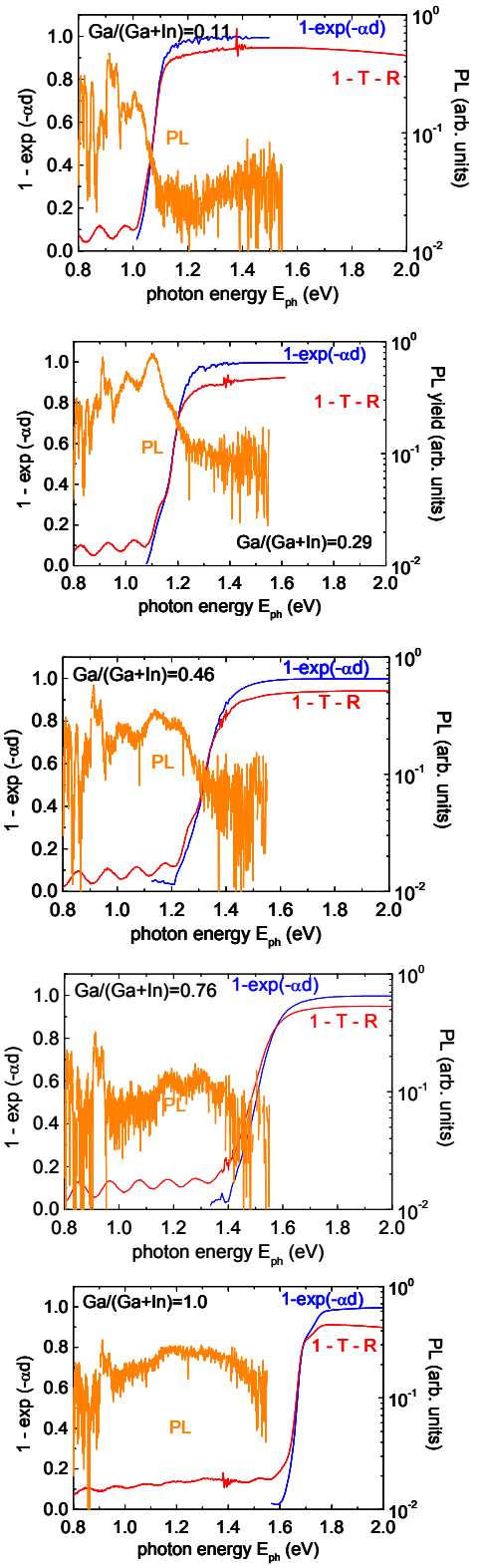
Splitting of Quasi-Fermi-Levels in $Cu(In_{1-x}Ga_x)Se_2$ by Room Temperature Photoluminescence

G.H. Bauer[a], R. Brüggemann[a], S. Vignoli[b]
[a] Inst. of Physics, Carl von Ossietzky University, D-26121 Oldenburg, F.R. Germany
[b] Lab. PMCN (CNRS UMR), Universite CB Lyon 1, F-69622 Villeurbanne Cedex, France

The splitting of Quasi-Fermi levels in $Cu(In_{1-x}Ga_x)Se_2$ absorbers and absorber-rear contact-window-layer structures with varying Ga contents in the regime $0.0 \leq x \leq 1.0$ has been studied with calibrated photoluminescence at room temperature and with AM1- equivalent photon fluxes. The CIGS samples have been prepared under pilot line production conditions with final cell efficiencies of up to 15 % [1].



Our PL data have been evaluated with respect to the chemical potential of the electron-hole ensemble $\mu_{n,p}=(\varepsilon_{F,n}-\varepsilon_{F,p})$ according to Planck's generalized law for the emission of non-thermal equilibrium radiation from matter in particular for the individual absorbers [2]. We have separated the Bose-Term $[\exp[(\hbar\omega-\mu_{n,p})/kT]-1]^{-1}$ by dividing the spectral pl-yield by the spectral absorptivity $A(\omega)\ \omega^2$ derived from spectral transmission/reflection measurement with an integrating sphere.

The spectral absorptivity for the polycrystalline CIGS shows non-negligible subgap absorption in the entire regime of composition ($0.1 \leq x \leq 1.0$) that indicates a substantial combined density of states at least partially located in the gap at energetic positions almost independent of Ga-admixture. In comparison to the shift of the band gap with increasing Ga concentration the luminescence peaks shift in energy only very weakly (figs.1a-1e, 2). Accordingly the energetic separation of the quasi-Fermi levels at room temperature, determining the maximum achievable open circuit voltage, only marginally increases, e.g. $\Delta\varepsilon_g$= (1.58-1.23)eV yields $\Delta(\varepsilon_{F,n}-\varepsilon_{F,p})$ = 0.14 eV, see fig.3).

Our studies clearly demonstrate that $(\varepsilon_{F,n}-\varepsilon_{F,p})$ versus ε_g is strongly limited by the density of those states responsible for the subgap absorption, which have been identified recently via photo capacitance spectroscopy as defect bands [3].

For an effective optimization of higher band gap CIGS cells in particular with respect to reasonable open circuit voltages, the reduction of the density of defects in the respective bands is the most critical issue.

Figs. 1a-e.
Spectral room temperature photoluminescence, experimentally monitored absorption (1-T-R, der lines), and absorption calculated via absorption coefficient (without subgap contribution) of $Cu(In_{1-x}Ga_x)Se_2$ absorbers (glass/ CIGS/CdS) with different Ga-contents x under excitation withAM1-equivalent photon fluxes for the determination of the energetic separation of quasi-Fermi levels.
The spectral PL does not shift in energy as expected from the rise in optical band gap.

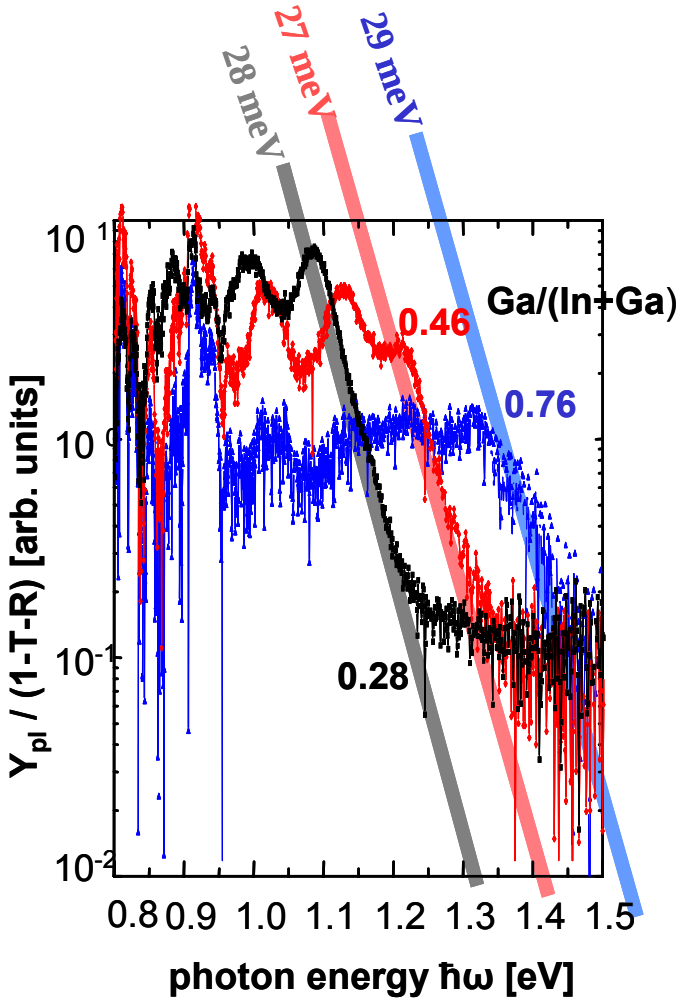


Fig.2.
Experimental Bose-terms [exp{(ħω-μ)/kT}-1]$^{-1}$ from spectrallly resolved room temperature photoluminescence in Cu($In_{1-x}Ga_x$)Se_2 absorbers (glass/CIGS/CdS) for the determination of the splitting of quasi-Fermi levels (maximum achievable V_{oc}). The departure of the experimental Bose-terms from theoretical ones (the effective emissivity does not equal the effective absorptivity) indicates a two phase system with different local life times and quasi-Fermi levels of minorities.

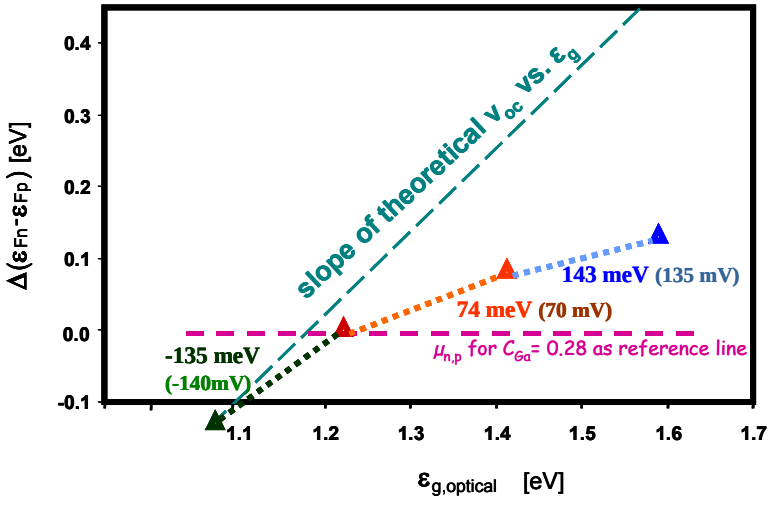


Fig.3.
Experimentally detected splitting of quasi-Fermi levels ($\varepsilon_{F,n}$-$\varepsilon_{F,p}$) in Cu($In_{1-x}Ga_x$)Se_2-absorbers (glass/ CIGS/CdS) from spectrally resolved room temperature photoluminescence at AM1 equivalent photon fluxes via Planck's generalized law with reference to v_{oc} of a CIGS-heterodiode with x= c_{Ga}=0.28 (numbers in brackets show respective v_{oc} of completed diodes (ZSW))

References

[1] M. Powalla et al., Proc. 14 EU PVSEC, ed. H. A. Ossenbrink et al., H. S. Stephens & Assoc. WIP-Munich,1997, p. 1270.

[2] P. Würfel, Physics of Solar Cells Physics, Wiley, 2004

[3] J.T.Heath, J.D. Cohen, W.N. Shafarman, D.X. Liao, A. Rockett, Appl. Phys. Lett. **80**, 4540 (2002).