Modulated photoluminescence for lifetime determination in passivated crystalline silicon wafers

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Overview

- Lifetime measurement
- Modulated Photoluminescence (MPL)
  - Concept
  - Experimental setup
- Some results
- Summary

Lifetime measurement

Established methods:

- Microwave photoconductance decay (µ-PCD)

- Quasi-steady-state photoconductance (QSSPC)

Problem: high concentration of free carriers (metallic defects, metallic rear contacts, high doped layers)

→ conductive methods fail because of shielding effects

→ alternative method: MPL

Concept: MPL

Δn: excess carrier density
G: genertation rate
R: recombination rate

- rate equation $$\frac{d\Delta n}{dt} = G(t) - R(t)$$

- modulated generation rate: $$G(t) = G_0 + G_1 e^{i\omega t} \qquad G_0 = R = \frac{\Delta n_0}{\tau_n}$$

- Ansatz: $$\Delta n(t) = \Delta n_0 + \Delta n_1 e^{i\omega t} \qquad \Delta n_1(\varphi) = |\Delta n_1| e^{i\varphi}$$

→ amplitude: $$|\Delta n_1| = \frac{\tau_n G_1}{\sqrt{1+(\omega\tau_n)^2}}$$

→ phase shift: $$\varphi = -\arctan(\omega\tau_n)$$

→ lifetime τ_n

Concept: MPL

Y_{PL}: Luminescence yield
n, p: carrier densities
$\Delta p = \Delta n$: excess densities
p_0, n_0: thermal eq. conc.
(d/dx)=0

$$Y_{PL} \propto R_{rad} \propto np$$

$$np = (n_0 + \Delta n)(p_0 + \Delta p)$$

$$\overset{p_0 \gg n_0}{\approx} \Delta n (p_0 + \Delta p) \approx$$

(case 1) $\overset{p_0 \gg \Delta n}{\approx} \Delta n \, p_0$

$$Y_{PL} \propto G^{\gamma} = G^{\beta+1}$$

assume $\tau \propto G^{\beta}$ $\longrightarrow$

(case 2) $\overset{p_0 \ll \Delta n = \Delta p}{\approx} \Delta n^2$

$$Y_{PL} \propto G^{\gamma} = G^{2\beta+2}$$

Excess density proportional to lifetime: $\Delta n = G \tau_{eff}$

Concept: MPL

Considering high quality wafers with high bulk lifetime, the effective lifetime is determined by the contribution of surface/passivation layers (recombination velocities):

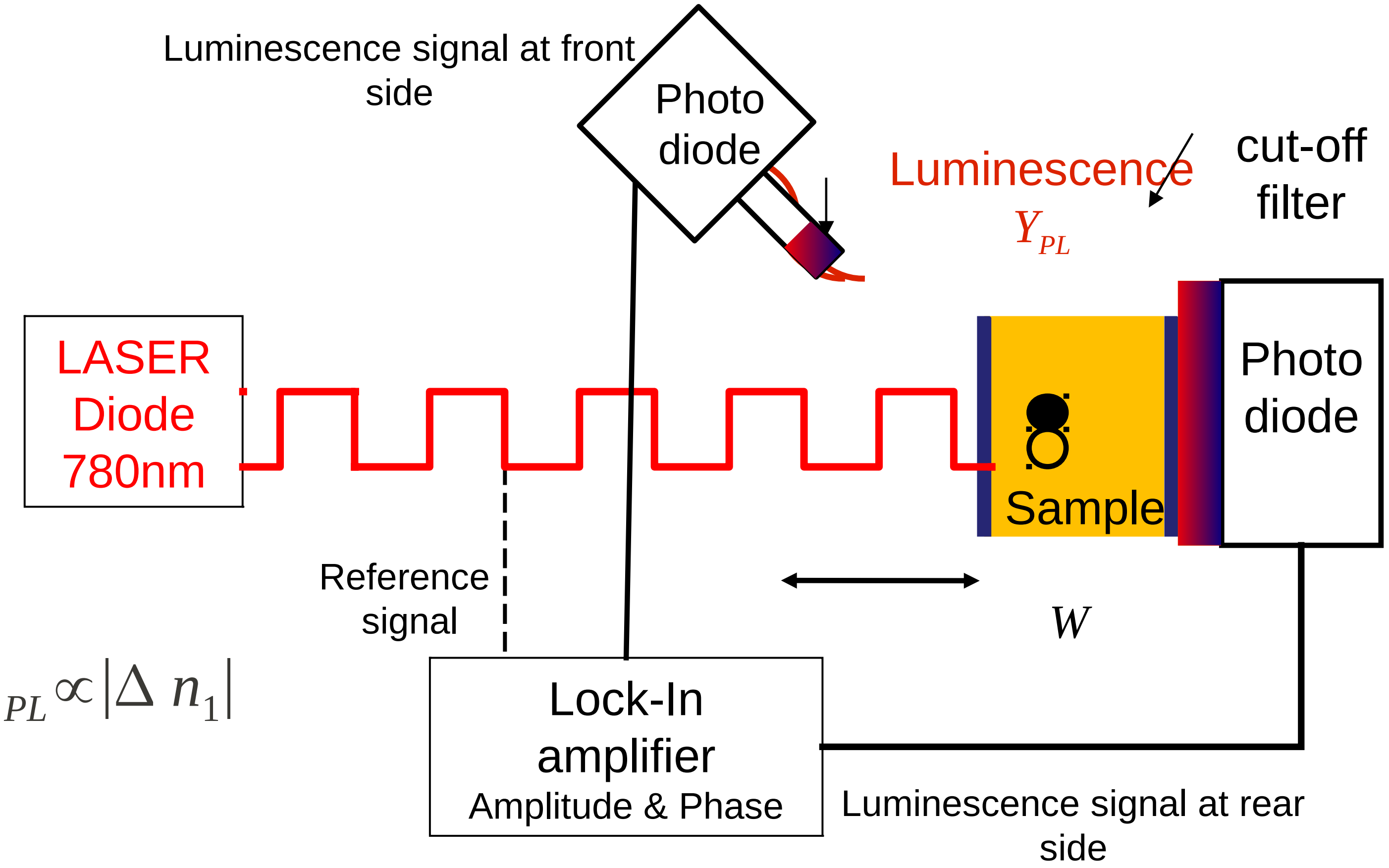
$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{bulk}} + \frac{S_{front}}{W} + \frac{S_{back}}{W} = \frac{1}{\tau_{bulk}} + \frac{2S}{W}$$

(symmetrical samples)

$$\frac{1}{\tau_{bulk}} = \frac{1}{\tau_{defect}} + \frac{1}{\tau_{Aug}} + \frac{1}{\tau_{rad}}$$

S: recombination velocities
W: wafer thickness

Experimental setup

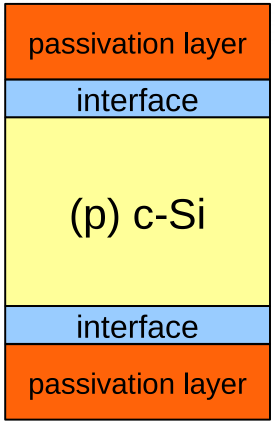


Amplitude: $Y_{PL} \propto |\Delta n_1|$

Phase: φ

Measurement at front and back side of sample possible

Samples

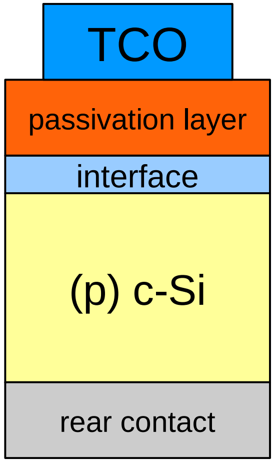


p-type c-Si wafer with different passivation:

- different passivation layers: n-type, intrinsic, SiC, a-Si:H, SiN

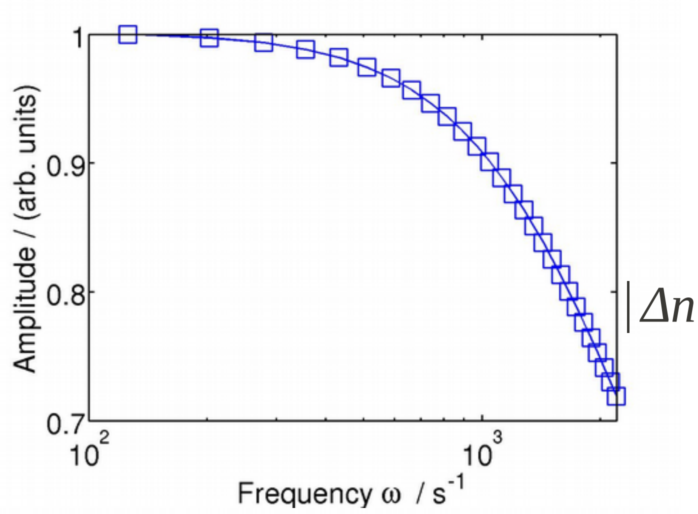
- different doping ($N_A=10^{15}$ cm^{-3}, $N_A=10^{16}$ cm^{-3})

- wafer with TCO and rear contact (solar cell)



Results: SiC-passivation (1 Ωcm)

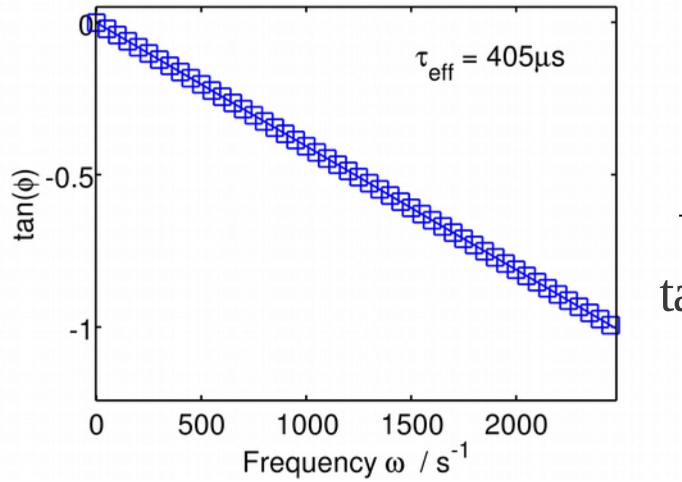
two procedures for lifetime extraction from experimental measurement



fit amplitude

$$\xrightarrow{}\quad \tau_n = 397\,\mu s$$

$$|\Delta n_1| = \frac{\tau_n G_1}{\sqrt{1+(\omega\tau_n)^2}}$$

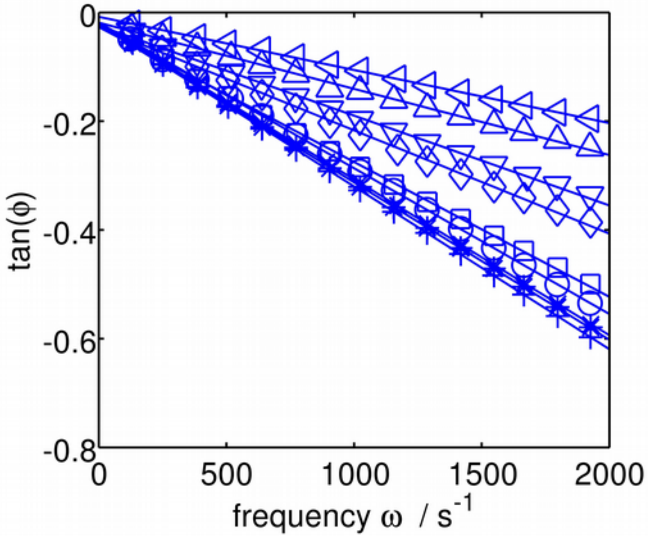


fit tangent

$$\xrightarrow{}\quad \tau_n = 405\,\mu s$$

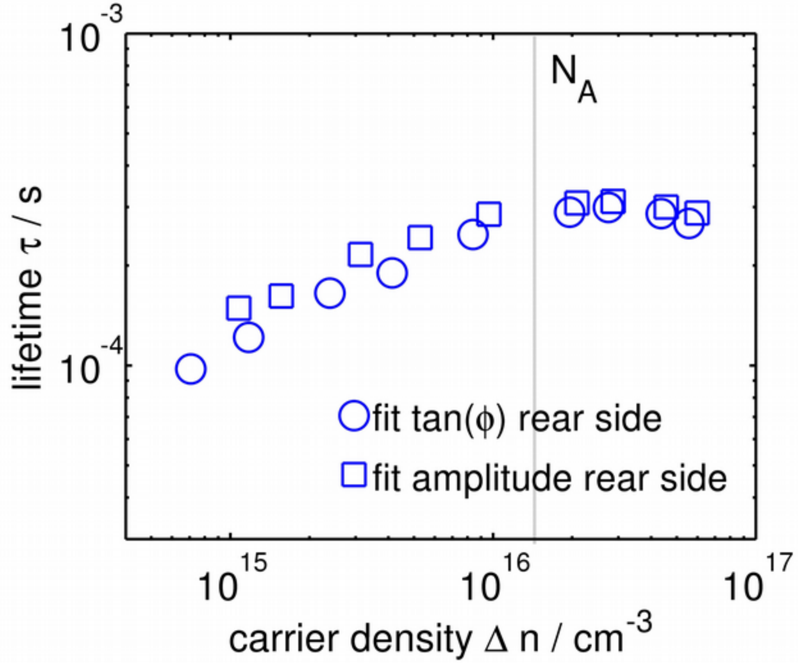
$$\tan(\varphi) = -\omega\tau_n$$

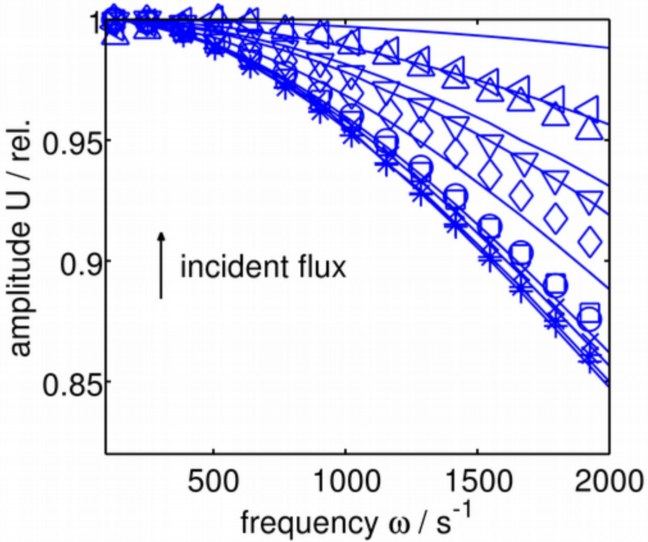
Results: SiN passivation (1 Ωcm)



lifetime measurement by phase more reliable in contrast to amplitude

τ_{ϕ}



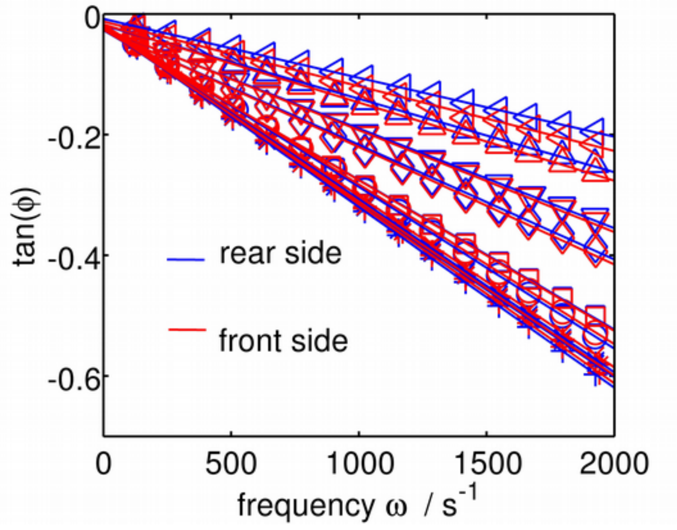


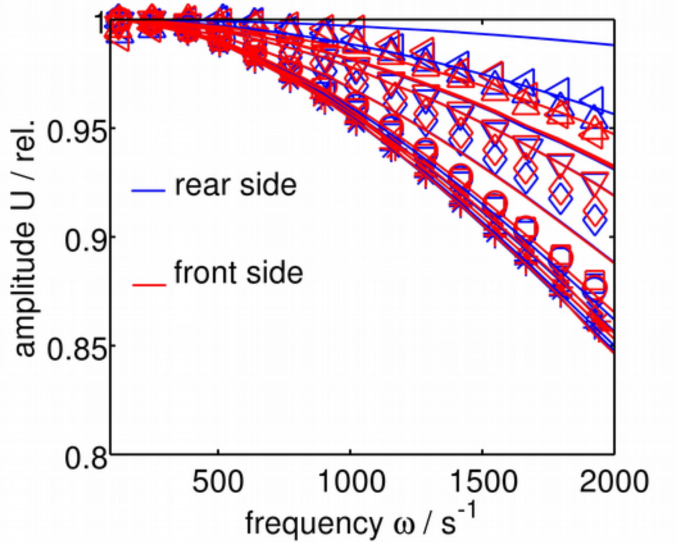
$\tau_{amplitude}$

$$\Delta n = G\tau_{eff}$$

Results: SiN passivation (1 Ωcm)

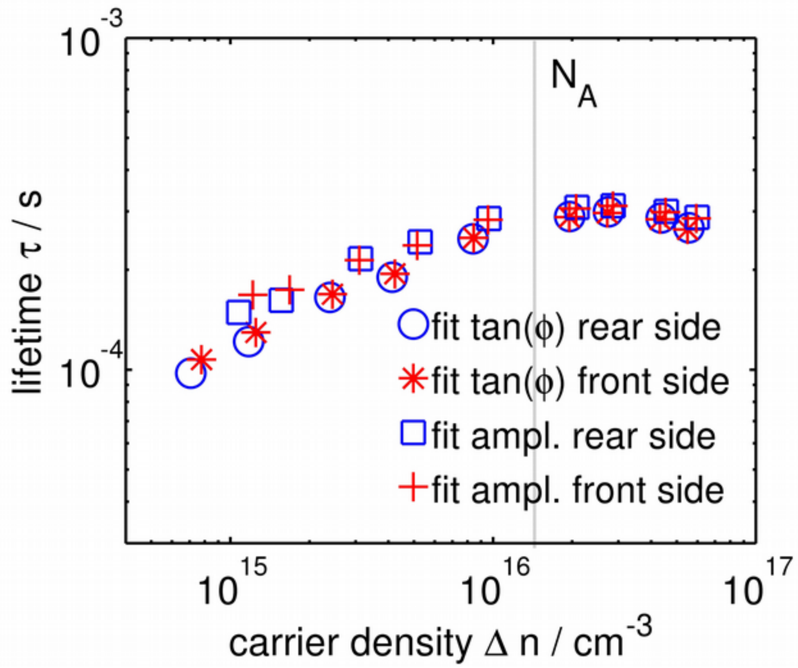
good agreement between measurement at rear and front side





τ_{ϕ}

$\tau_{amplitude}$

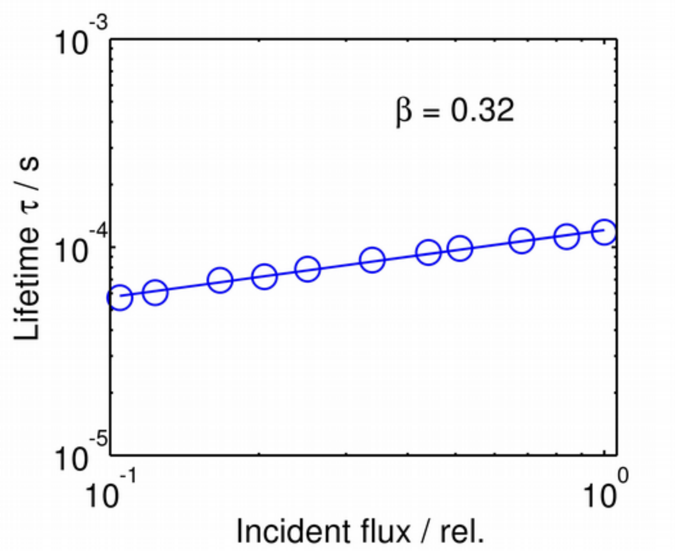


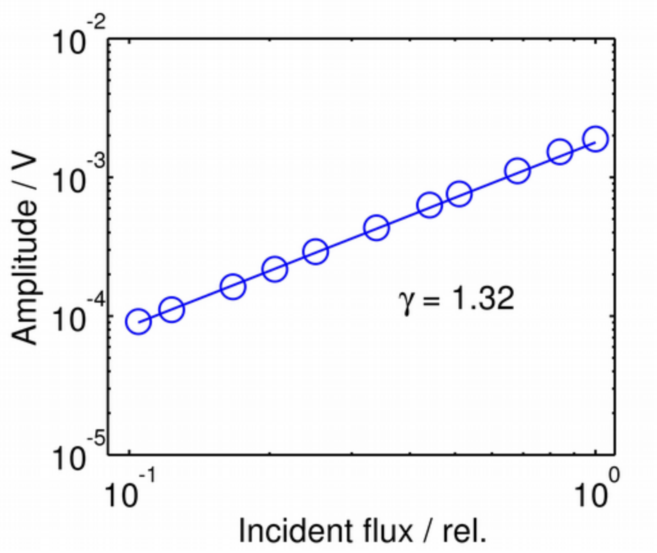
$$\Delta n = G\,\tau_{eff}$$

Results: (i)a-Si:H passivation (1 Ωcm)

Lifetime and amplitude depend on incident flux by power law (in regimes of high doping)

Power-law relation between lifetime and amplitude





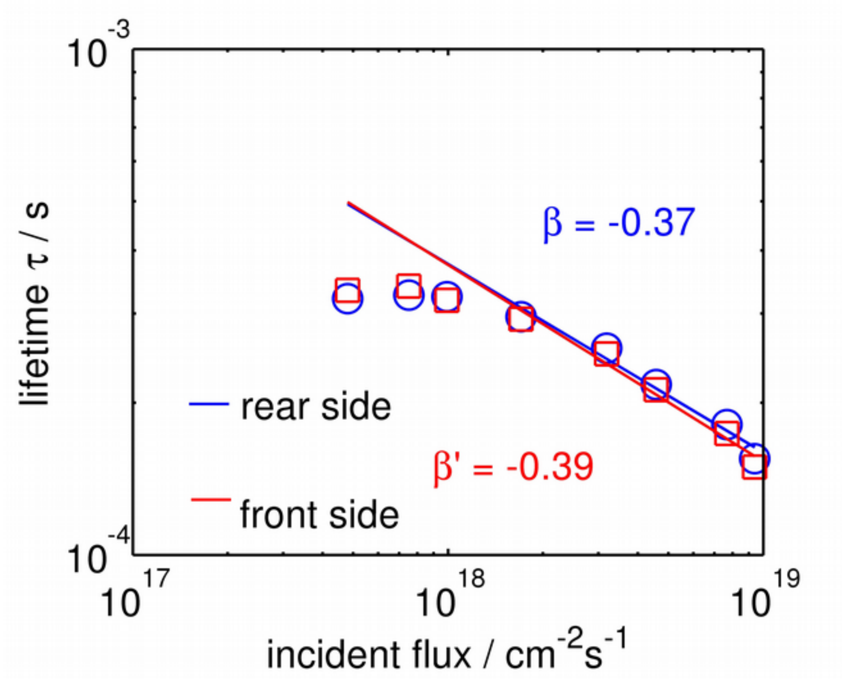
$$\gamma = 1 + \beta$$

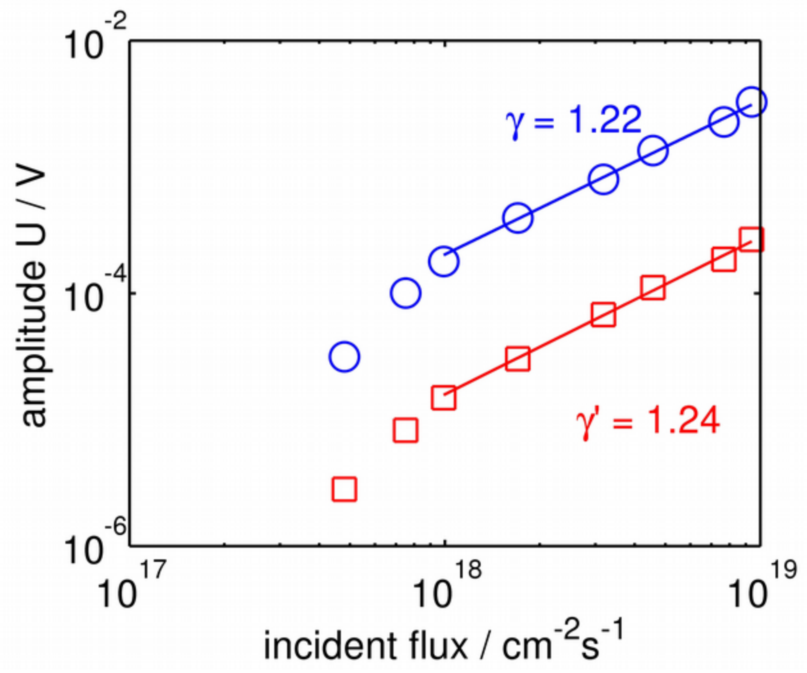
$$\tau \propto G^{\beta} \longleftrightarrow Y_{PL} \propto G^{\gamma}$$

Results: (i)a-Si:H/(n)a-Si:H pass. (14 Ωcm)

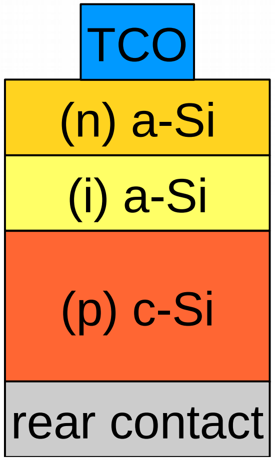
Sample with low doping ($N_A = 10^{15}\mathrm{cm}^{-3}$) → in regimes of high excitation the powerlaw-relation between lifetime and amplitude is described by

$$\gamma = 2 + 2\,\beta$$





Results: Cell



TCO

(n) a-Si

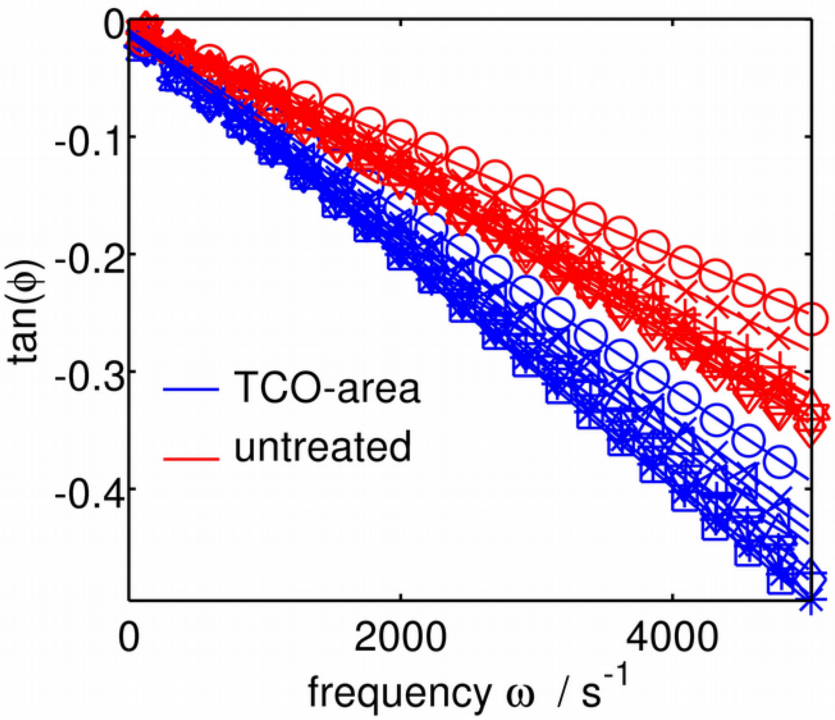
(i) a-Si

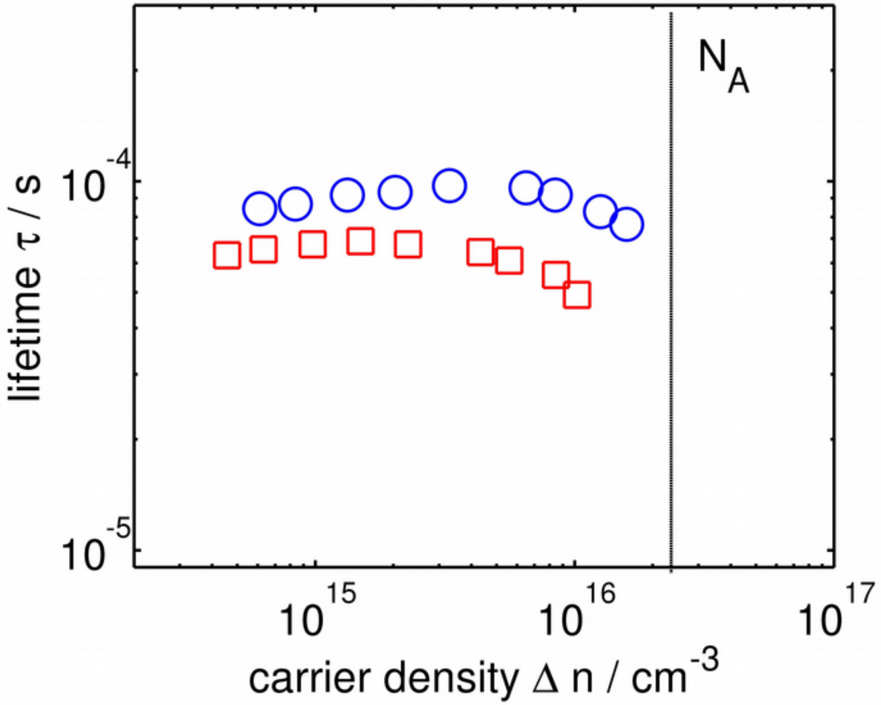
(p) c-Si

rear contact

a-Si passivated p-type wafer (1 Ωcm, $N_A = 10^{16}$ cm^{-3}) with TCO

MPL allows measurement on bare wafer and TCO-texture (via small excitation spot)





Summary

- Modulated photoluminescence promises an efficient method for effective lifetime measurement

- MPL is a useful tool for the investigation of a wide range of species of wafers with any passivation

- Advantage of MPL to other lifetime measurements: phase shift allows also investigation of wafers and cells with high doping and backcontacts