Characterization of irradiated silicon structures by microwave absorption techniques

E.Gaubas, J. Vaitkus

OUTLINE

- ***Motivation of direct control of carrier decays***
- ***Measurement regimes: MWA/R - slit antenna, MWR - coaxial cable needle probe***
- ***Evaluation of carrier decay parameters***
- ***Excess carrier decay temperature variations***
- ***Comparison with DLTS data in e-irradiated diodes***
- ***Summary***

Why lifetime direct control?

- In the irradiated material different types of defects appear: some of them are important in formation of the space charge, while other are prone to transform and “wait” to become active
- Control of the defect types in the sample can be performed by using the direct methods by stimulating defect manifestation, varying measurement regimes and the most important external factors, e.g. λ_{exc}, BI, T, I_{exc} etc.

- The light pulse is a mean to force the defect system to react and the conductivity change can be detected.

- Any change of the system of defects can be revealed: the main difficulty is to interpret the situation, e.g. whether there is transform of traps or a new channel of competition between traps and recombination centers.

- Our activities - to design the instruments for analysis of peculiarities of photoresponse and to suggest the methods of extracting the valuable information from the measurement data.

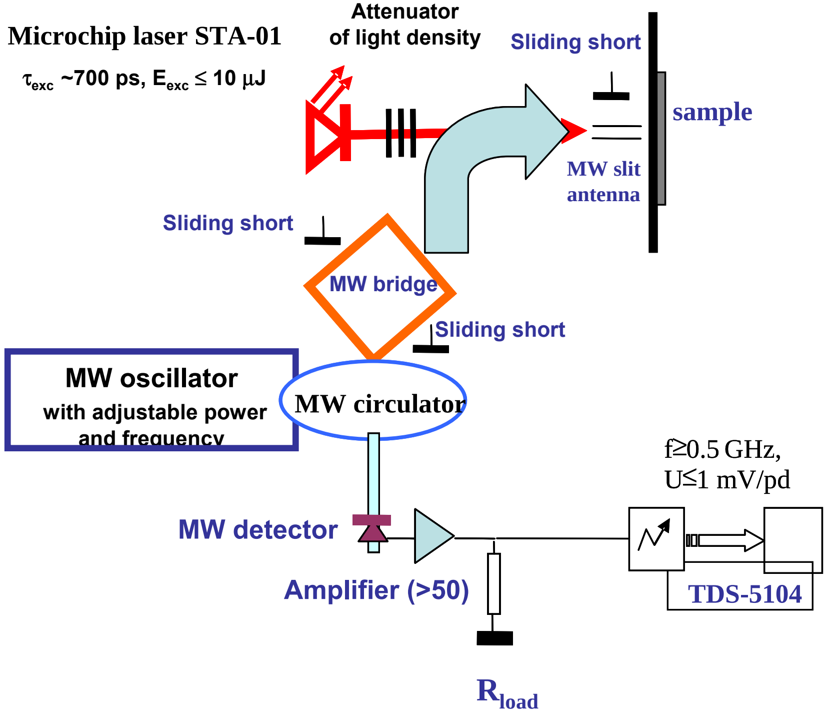
Motivation of non-invasive direct transient techniques

☼ PC measurements can be implemented by using contacts (TCT) or by contact-less probe - microwaves.

☼ Contacts and polarization of sample under bias involve additional problems. Microwave methods are free of contact problems, thus, enabling one to examine the decay temperature variations in order to extract the activation energy of the recombination and trapping centers, to correlate with parameters estimated by electrical methods as DLTS.

☼ The non-invasive contact-less methods can be implemented by using distant measurements, thus, can be applied to control the parameters of detector material just after the irradiation or even during irradiation.

Analyser of the recombination parameters



Microchip laser STA-01

τ_{exc} ~700 ps, $E_{exc} \leq 10$ μJ

Attenuator of light density

Sliding short

sample

MW slit antenna

Sliding short

MW bridge

Sliding short

MW oscillator

with adjustable power and frequency

MW circulator

f≥0.5 GHz,
U≤1 mV/pd

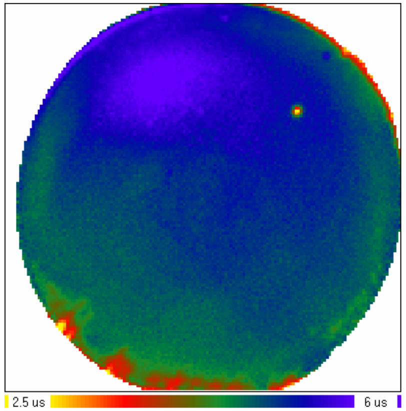
MW detector

Amplifier (>50)

TDS-5104

R_{load}

Round Robin calibration of the MWR instruments by using Ge, Si

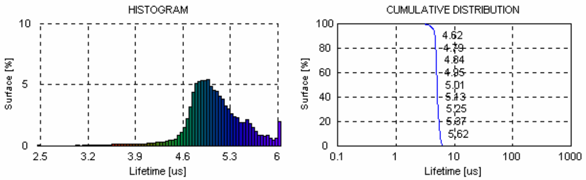


Si *Phoenicon (Germany),*

Si, Ge *Phoenicon-Amecon (IMEC, Belgium),*

Si, Ge *Semilab WT-85X (Umicore, Belgium)*

Si, Ge *VUTEG-2 Vilnius*

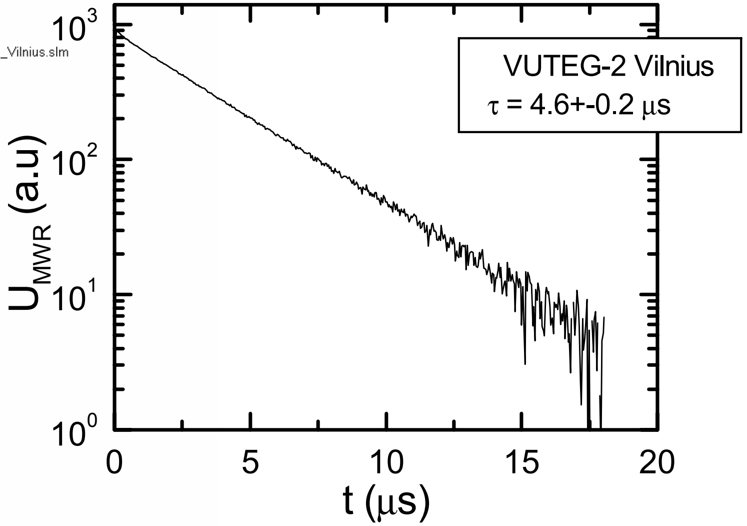


Filename: \\HPSERVER301\User\Manole\110_oxidized_Vilnius.slm
Comment: after oxidation Vilnius 110 Si
Date/Time: 19.07.2005 09:53
Operator: MM
Sample: 110 Vilnius
Raster: 500 um
Size: 3 inch
Scanradius: 38.05 mm, 37.29 mm

🟩 u-PCD

Lifetime:
Average: 5.053 us
Median: 5.0528 us
Deviation: 8.965 %
Minimum: 1.803 us
Maximum: 6.58 us

Time Range: 0.1 ms
Time Cursor: Auto
Sensitivity: 100 mV
Averaging: 64
MW Freq.: 10.489 GHz
Laser Power: 120 E10
Pulse Width: 200 ns
Bias Lamp Power: 926 mSun
Laser Wavel.: 904 nm
Head Height: 0 mm



Samples and irradiations

☼ ***Samples investigated for inter-instrument carrier lifetime calibration:***

I.1. MCZ Si sample 20×5×5 mm^3 with two surfaces polished. This sample of about 6 kOhm cm resistivity is mounted with load resistor for simultaneous control of contact photoconductivity.

I.2. Phosphorous doped Cz Si 20×5×5 mm^3 sample with two surfaces polished.

I.3. Phosphorous doped Cz Si 5 mm thick half-wafer with polished surfaces.

I.4. Borum doped Cz Si Cz Si 5×5×5 mm^3 sample with two surfaces polished.

I.5. Borum doped Cz Si 5 mm thick half-wafer with polished surfaces.

I.6. MCZ n-Si wafer piece of 20×20×0.28 mm^3 dimensions. Surfaces are passivated by thermal oxidation.

I.7. N-type Ge 352-3 wafer of 500 μm thickness with polished, varnish passivated surfaces.

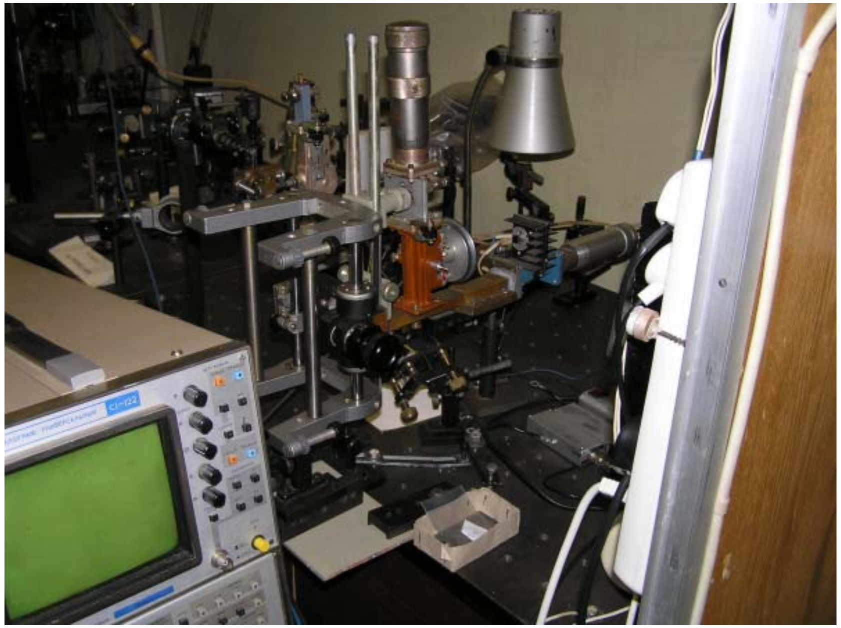
I.8. P-type Ge 327-4 wafer of 500 μm thickness with polished, varnish passivated surfaces.

☼ high resistivity MCZ and FZ silicon wafers and diode structures

☼ irradiated by high energy electrons, γ-rays, and protons

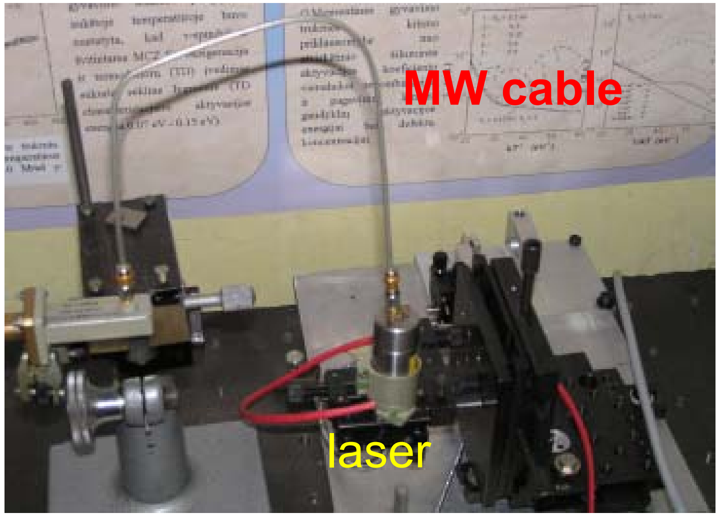
Measurement instruments available at VU: MWA & MWR - slit antenna, MWR - coaxial needle-tip probe, DLS-82

MWA 10 GHZ probe



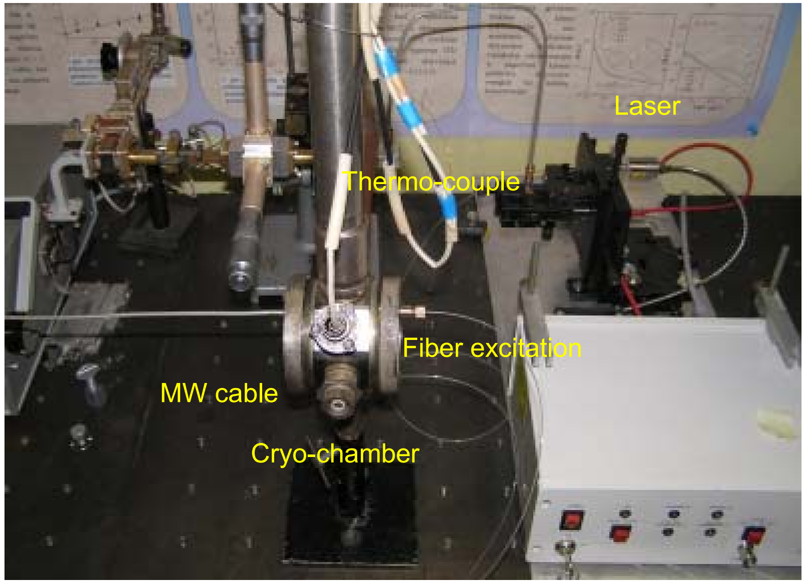
MWR 22 GHZ probe

slit antenna probes

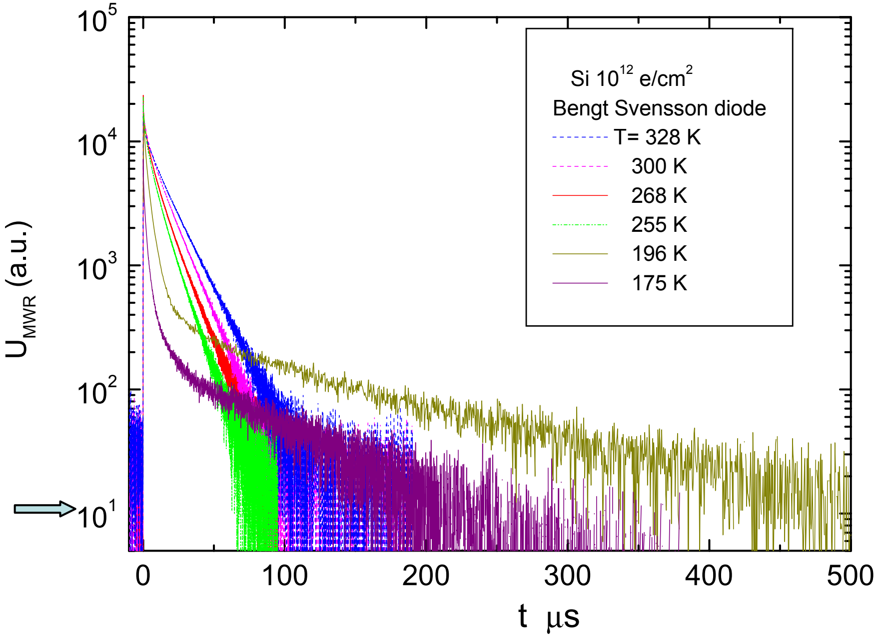


Microwave coaxial needle-tip antenna probe

Cryogenic microwave needle tip -antenna probe integrated with the fiber excitation probe

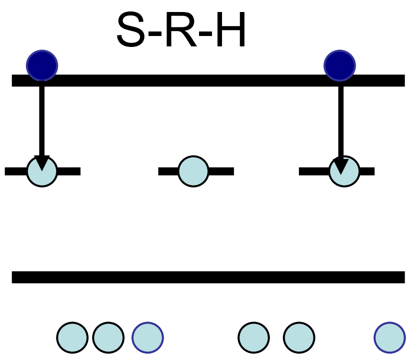


MWR transient variations with temperature in Si diode irradiated with electrons of fluence 3*10^{12} e/cm^2



Dominant single level

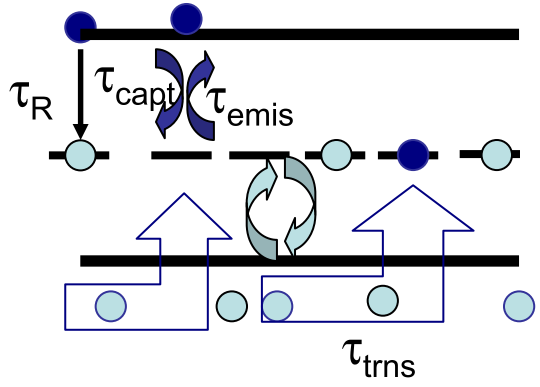
Low defect concentration



Carrier pair decay lifetime

High defect density

Blackmore recombination-trapping



Different e & h decay lifetimes,

while the effective lifetime is the longest of

τ_{capt}, τ_{trns}, τ_{emis}

$$\tau_{R,\ S\text{-}R\text{-}H}=[\tau_{cp}(n_0+n_{ex}+N_C e^{-(Ec-Em)/kT})+\ \tau_{cn}(p_0+n_{ex}+N_V\ e^{-(Em-Ev)/kT}\ )]/[n_0+p_0+n_{ex}]$$

$$\tau_{g,\ S\text{-}R\text{-}H}=[\tau_{cp}N_C e^{-(Ec-Em)/kT}+\ \tau_{cn}N_V\ e^{-(Em-Ev)/kT}\ ]$$

$$\tau_{g,\ S\text{-}R\text{-}H}>>\tau_{R,\ S\text{-}R\text{-}H}$$

$$s_{R,\ S\text{-}R\text{-}H}=\ s_n s_p[n_{0s}+p_{0s}+n_{exs}\ ]/[s_n(n_{0s}+n_{exs}+N_{it,c}e^{-(Ec-Eit)/kT})+\ s_p(p_0+n_{ex}+N_{Vit}\ e^{-(Eit-Ev)/kT}\ )]$$

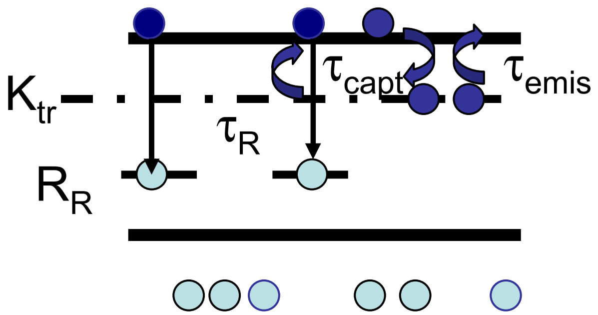
$$s_{g,\ S\text{-}R\text{-}H}=\ s_n s_p/[s_n N_{it,c}e^{-(Ec-Eit)/kT}+\ s_p N_{Vit}\ e^{-(Eit-Ev)/kT}\ ]$$

$$s_{g,\ S\text{-}R\text{-}H}<<\ s_{R,\ S\text{-}R\text{-}H}$$

$$s_{n,p}=\sigma_{n,p\ s}vN_{it}=\sigma_{n,p\ s}v\ kT\ D_{it}$$

System of two competing levels

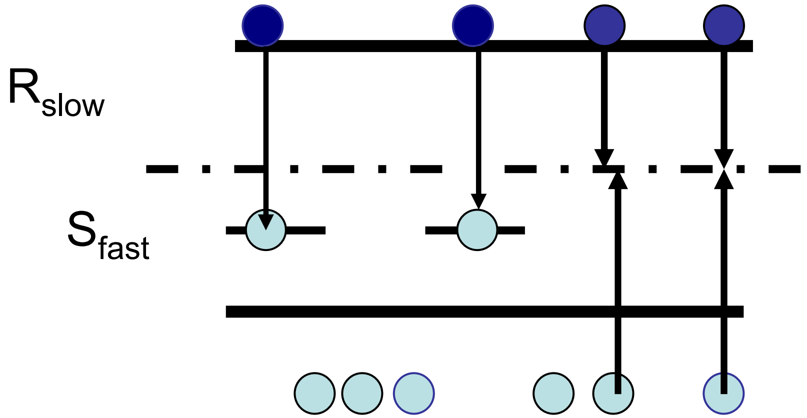
System of recombination-trapping centers Ryvkin' model



Carrier decay instantaneous lifetime

$$\tau_{inst} = \tau_R K_{tr} \approx \tau_R(1 + \tau_{gen}/\tau_{capt})$$

System of recombination centers with different rates Lashkarev' model

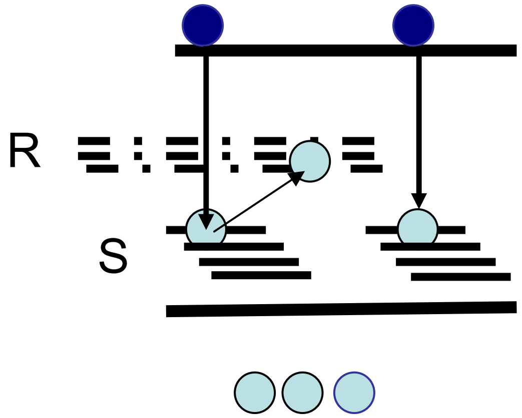


Carrier decay instantaneous lifetime

$$\tau_{inst} = - \ n/(dn/dt) \approx (A_S e^{-t/\tau s} + A_R e^{-t/\tau R})/(\tau_S^{-1} A_S e^{-t/\tau s} + \tau_S^{-1} A_R e^{-t/\tau R})$$

Systems of competing levels

Systems of recombination centers
Rose’ model

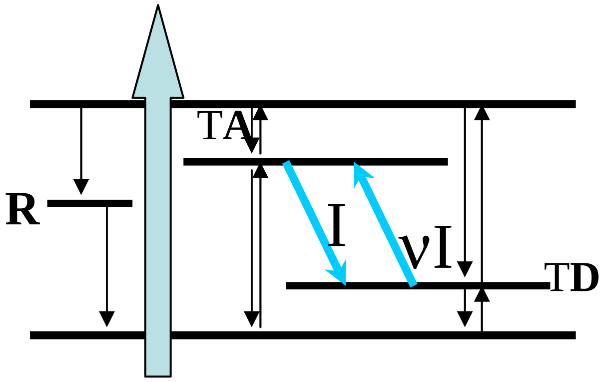


Carrier decay instantaneous lifetime

photoconductivity quenching etc. qualitative analysis

Systems of recombination centers

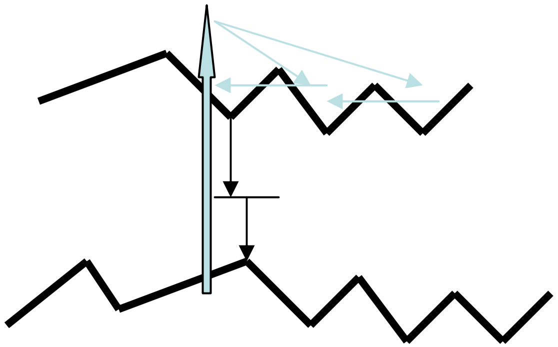
W.M.Chen, B.Monemar, E.Janzen, J.L.Lindstrom &*Watts’ model*



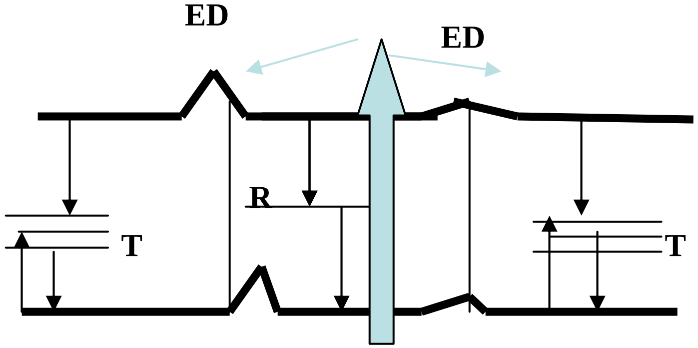
Inter-trap recombination

K.Takarabe, P.T.Landsberg, J.K.Liakos. Semic. Sc.Techn.(1997)
W.M.Chen, B.Monemar, E.Janzen, J.L.Lindstrom. Phys.Rev.Lett. (1991)

More complicated recombination-trapping processes

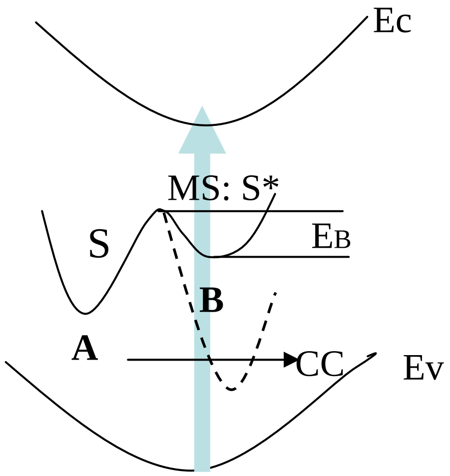


Carrier escape and motion barriers

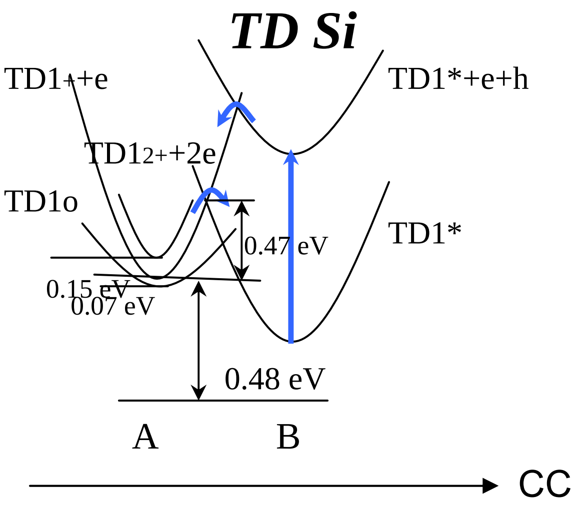


Extended defects: clusters, SiO_x precipitates, disorder etc.

G.Pfister,H.Sher Adv.Phys1978), P.T.Landsberg. Rec. Semic.(1991),
S.Havlin, D.Ben-Avraham. Adv. Phys. (2002)



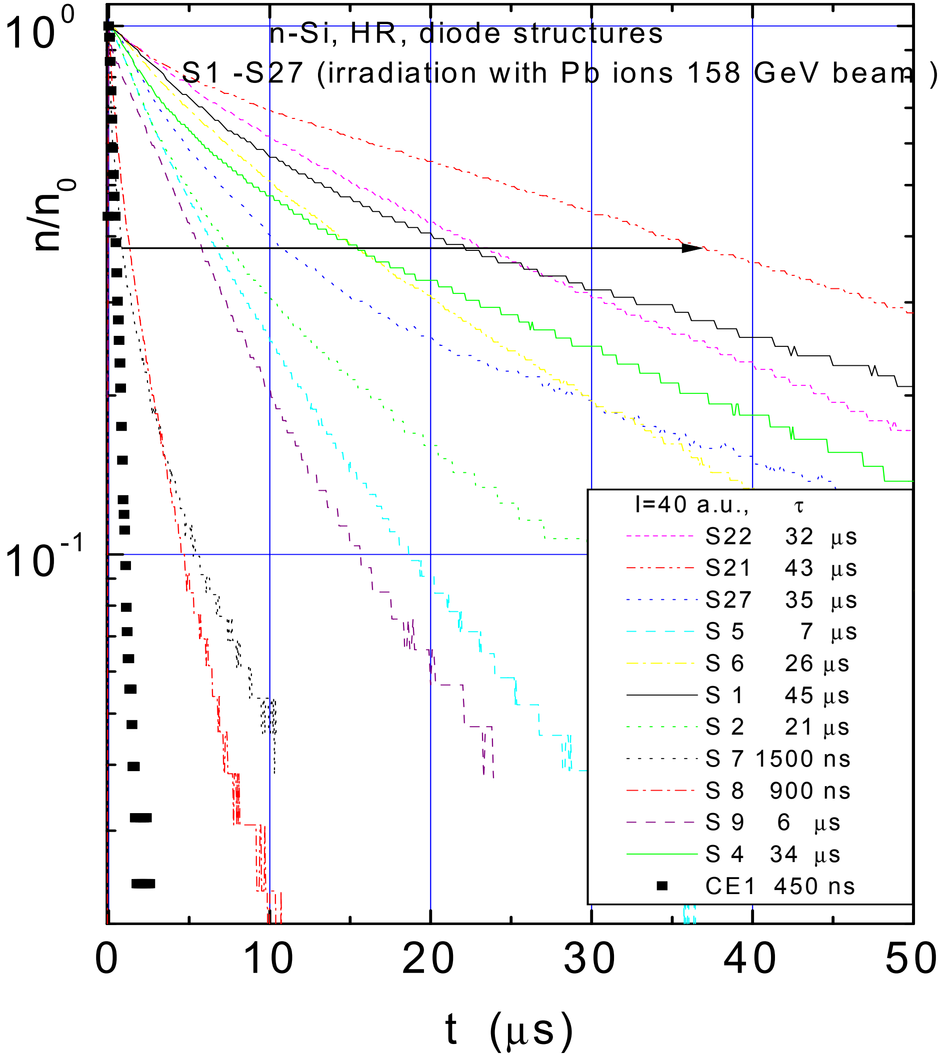
Metastable centres V-O, TD, etc.



G.Watkins SST(1991)
A.Chantre Appl.Ph.A(1989)

Carrier recombination

☼ *Recombination in the heavy irradiated material* *(nearly mono-exponential transients)*

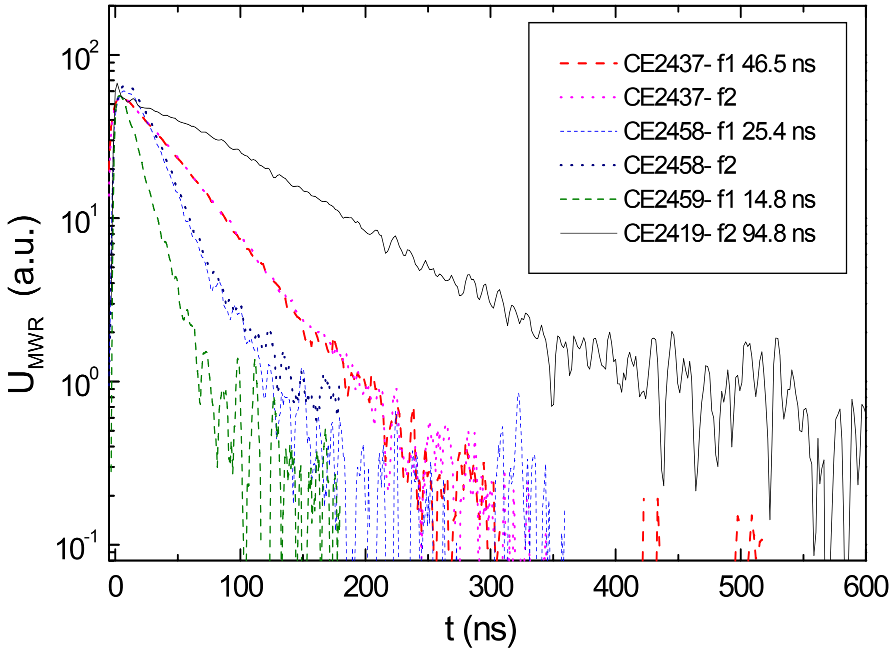


Carrier recombination

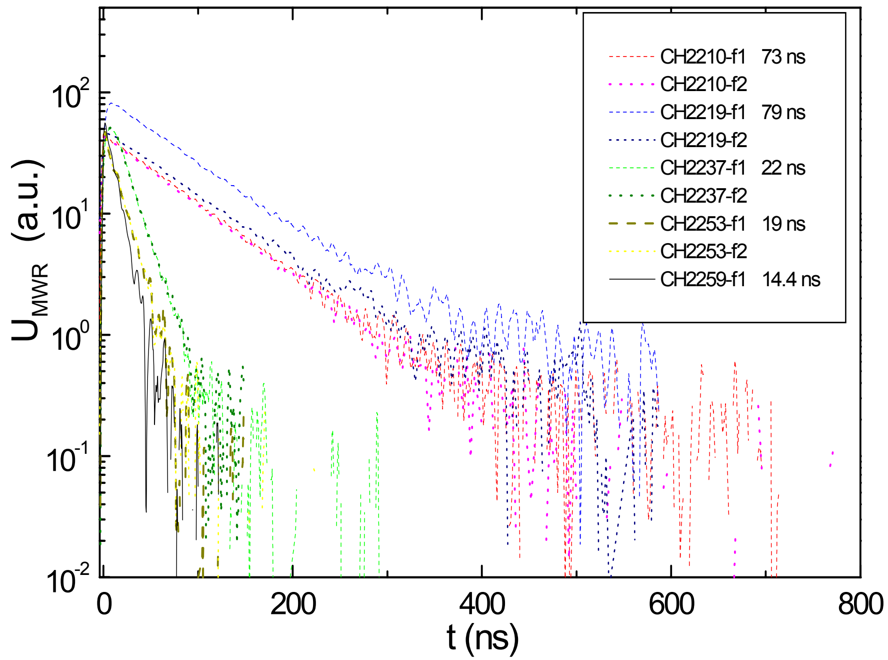
Excess carrier decay transients in proton irradiated diodes.
Material: Wacker FZ Si, <100>, 6kΩ cm

Diodes processed:

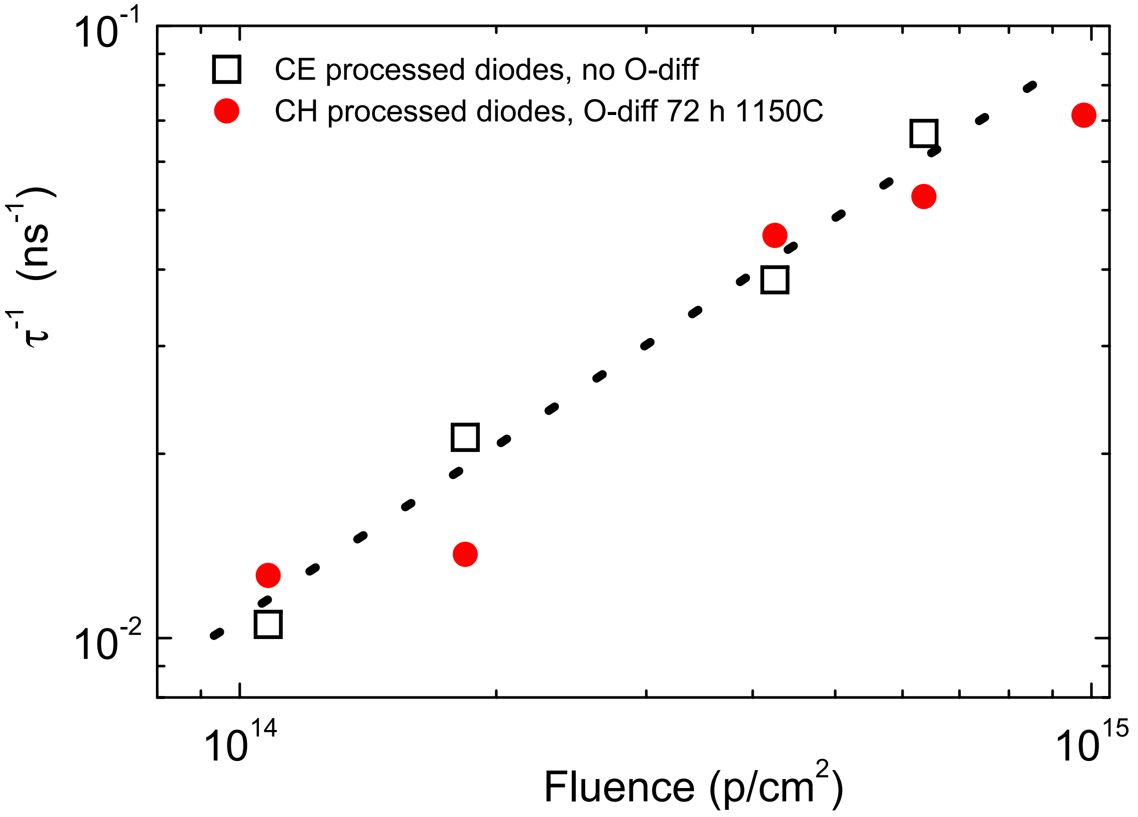
CIS CE O-diff no



CIS CH O-diff 75hN2 1150C



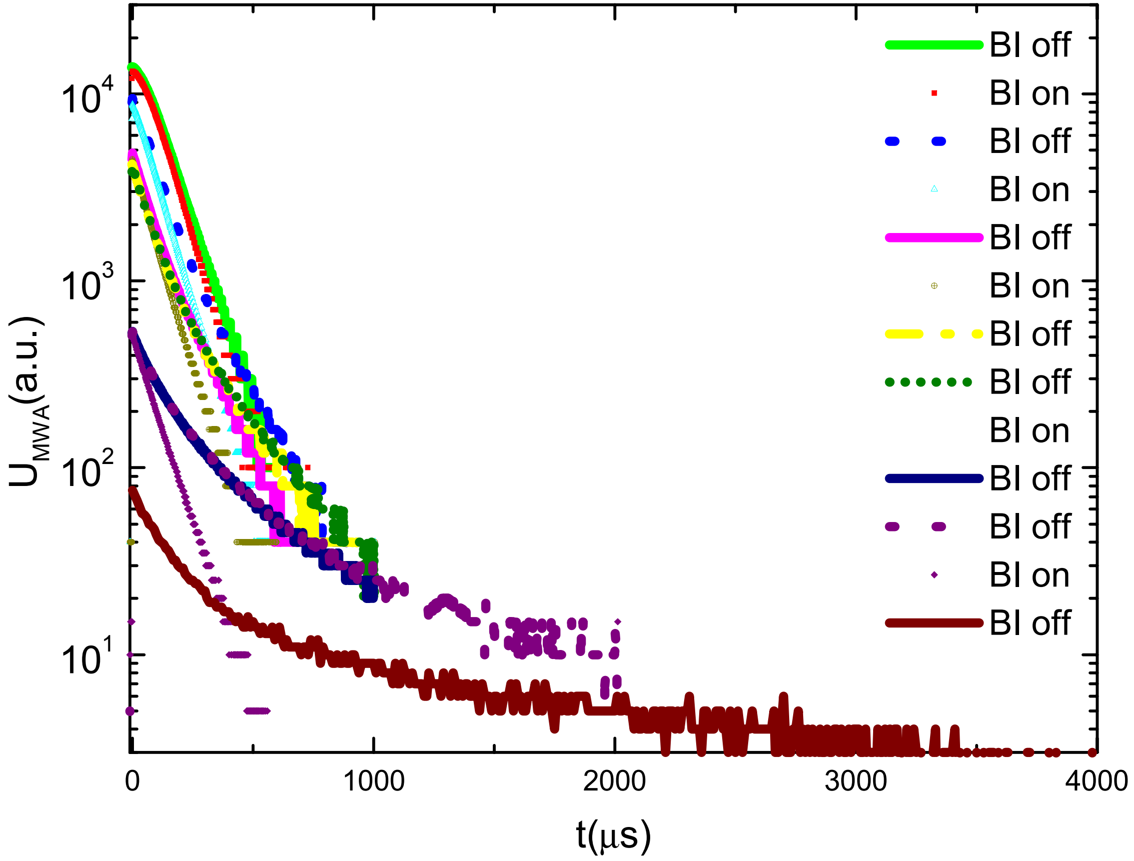
Carrier recombination



Decay lifetime dependence on irradiation fluence

Carrier recombination and trapping

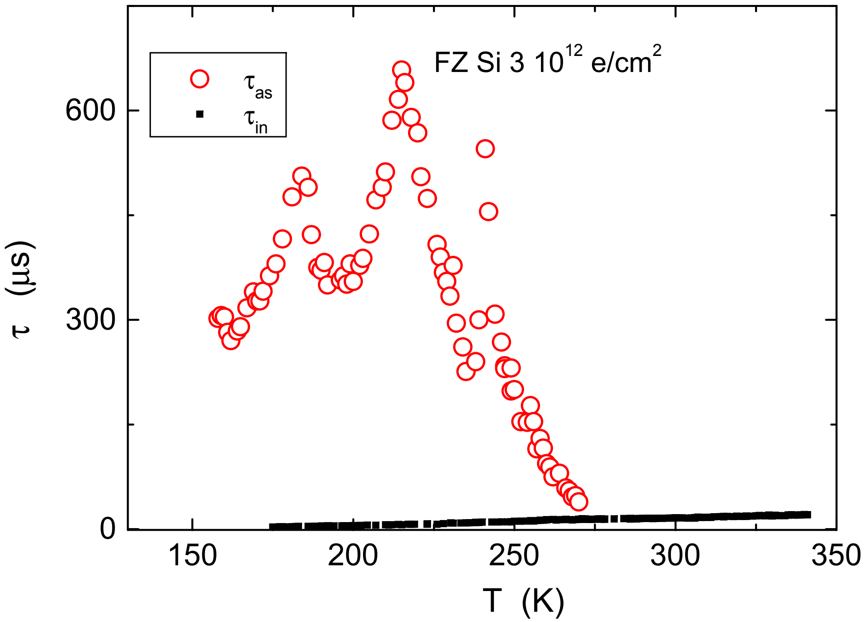
☼ Recombination (fast) and trapping (slow) constituents within transients of microwave absorption by free carriers (MWA) have been distinguished by combining analyses of the excess carrier decays dependent on the excitation intensity and bias illumination (BI).



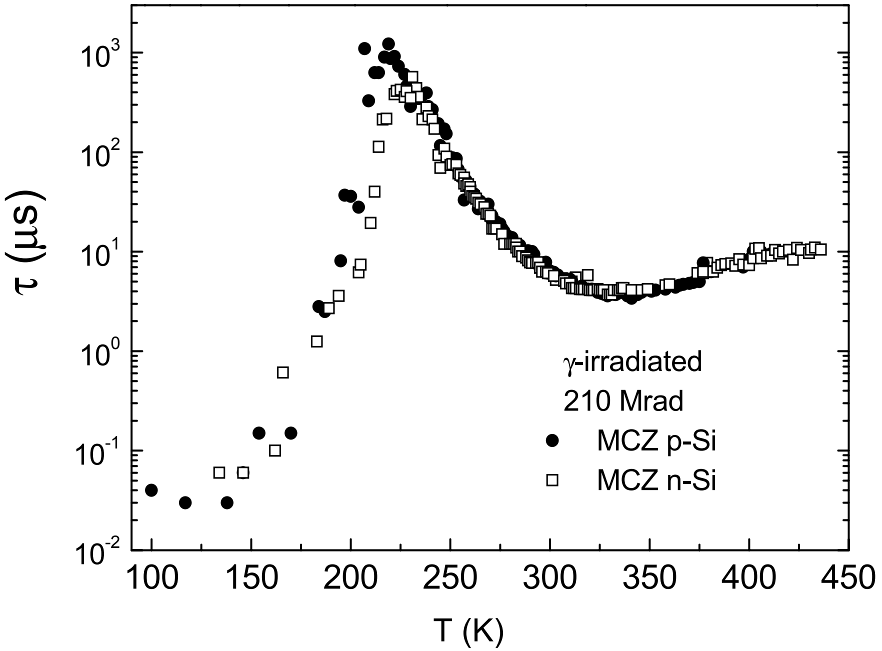
Variation of MWA decays with excitation intensity (proportional to the initial amplitude) with and without additional cw illumination

Excess carrier decay temperature variations

MWR coaxial needle-tip probe
e-irradiated FZ Si

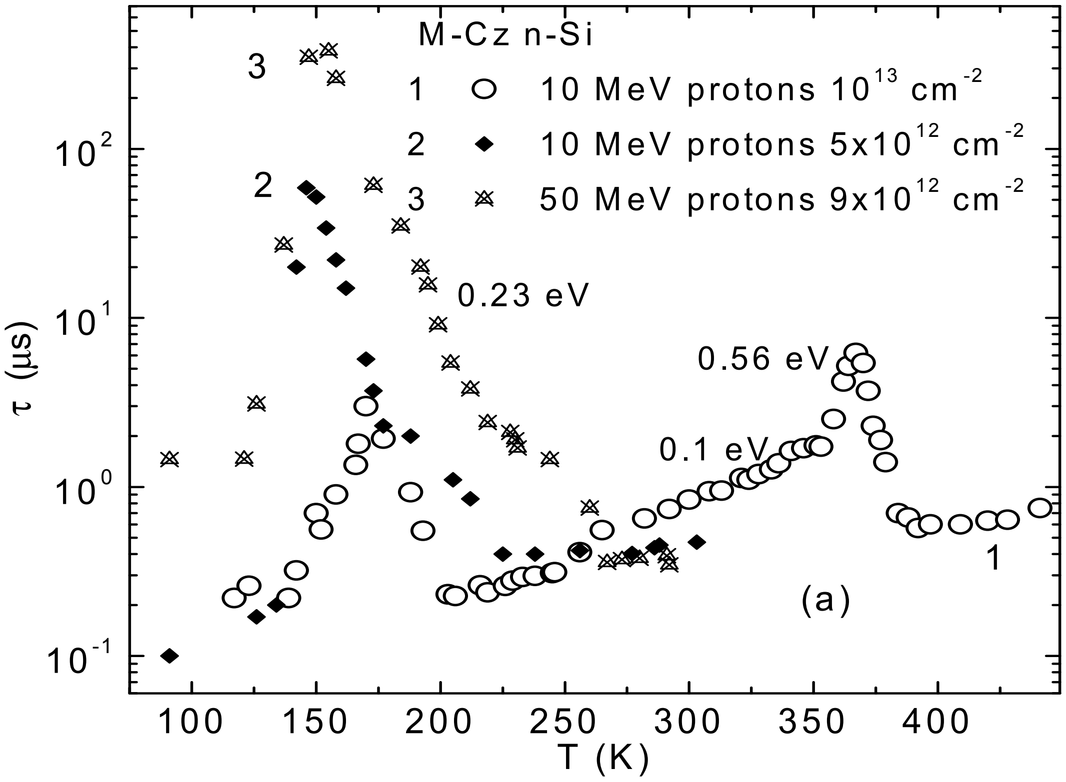


MWA slit antenna
γ-irradiated MCZ Si

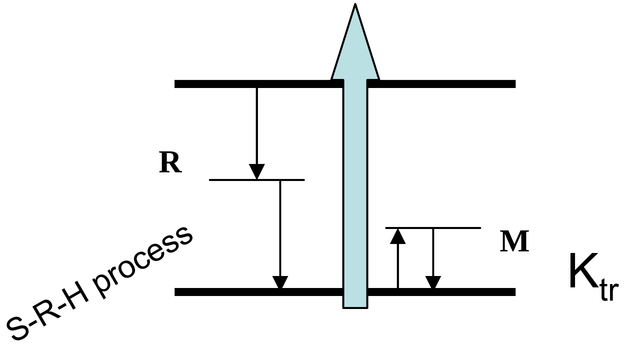


Excess carrier decay temperature variations

MWR proton-irradiated FZ Si



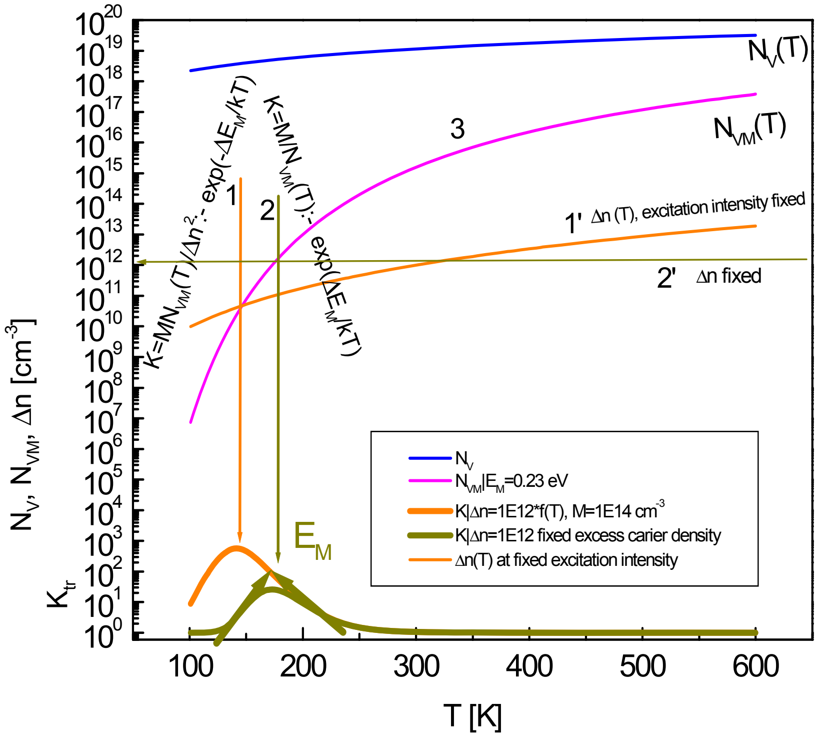
Qualitative simulation of the temperature dependent lifetime variations



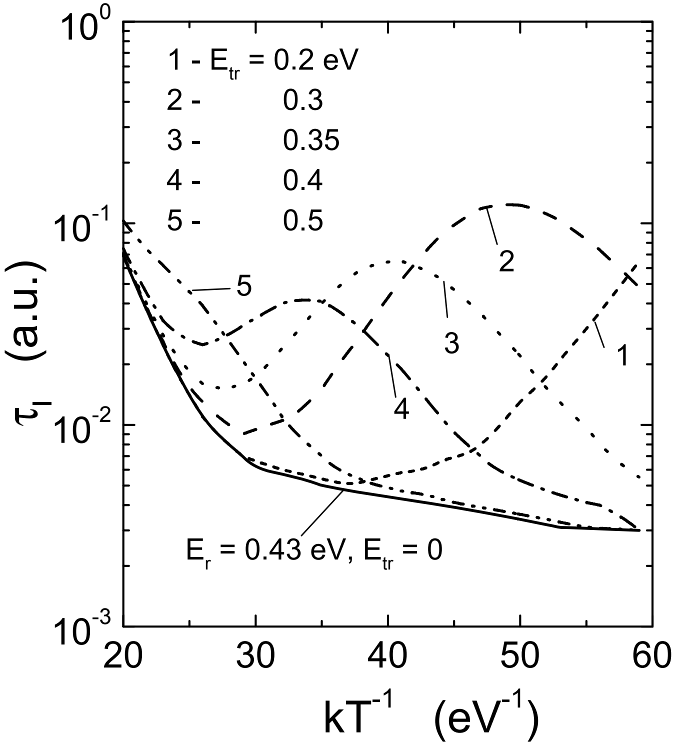
$\tau_{inst} = \tau_R K_{tr}$ (1),

$K_{tr}=[1+M N_{VM}/(N_{VM}+\Delta n)^2]$ (2)

$N_{VM}=N_V \exp(-\Delta E_M/kT)$



Variation of trapping coefficient K_{tr} with temperature, and formation of lifetime extrema at either fixed excess carrier density or for invariable excitation intensity



Variation of instantaneous lifetime with trap level position vs. inverse thermal activation factor at simultaneous recombination and trapping

Comparison with DLTS data in e-irradiated diodes

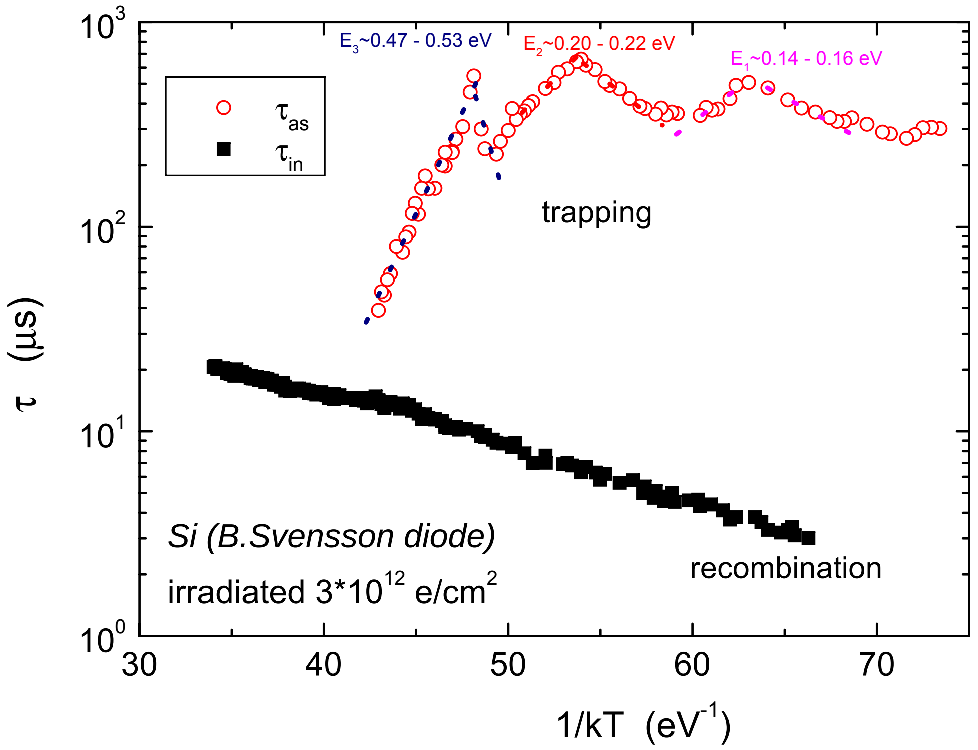


Fig. 1. Level activation energy determined by τ (T) characteristics in Si diode irradiated with electrons of fluence of 3*10^{12} e/cm^2 by employing MWR

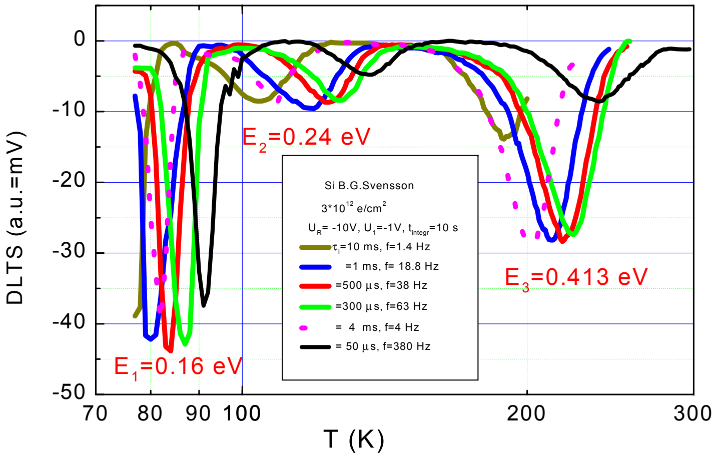


Fig. 2. Capacitance DLTS spectra measured in Si diode irradiated with electrons of fluence of 3*10^{12} e/cm^2 by employing the temperature scan regime for different lock-in frequencies.

DLTS

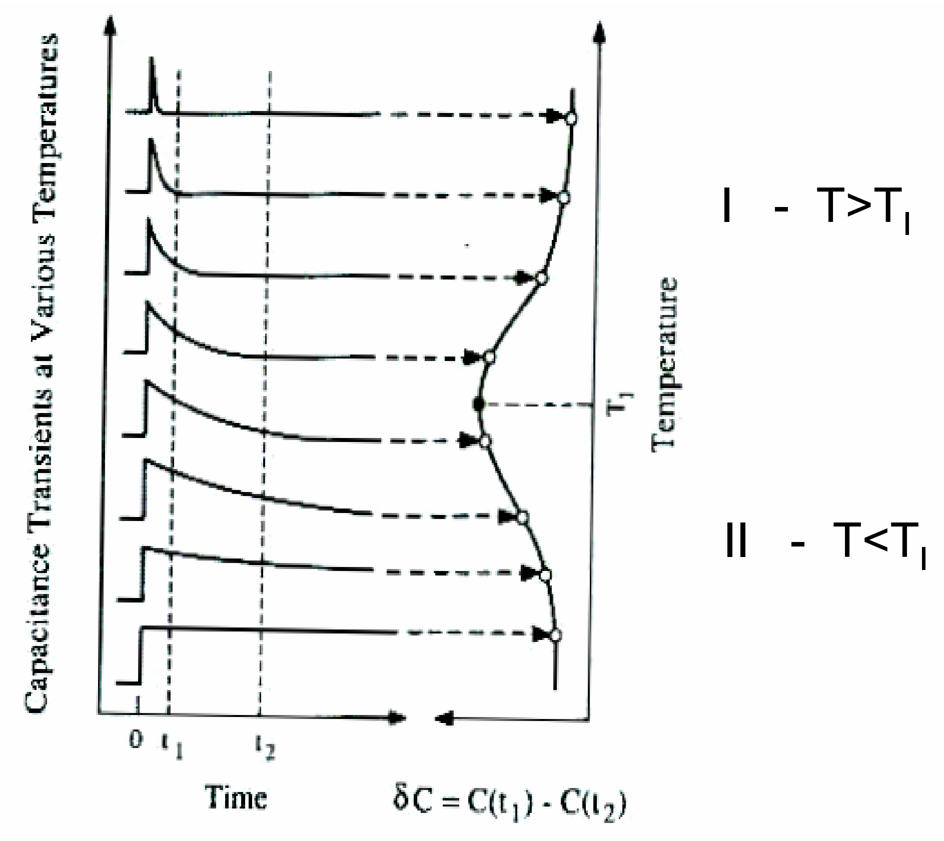
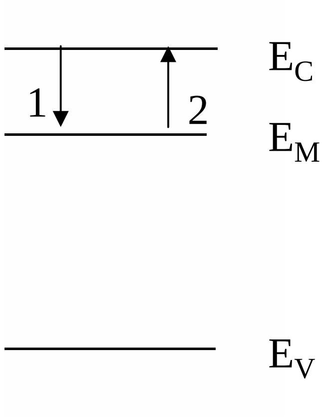


Fig. 7.11 Implementation of a rate window by a double boxcar integrator. The output is the average difference of the capacitance amplitudes at the sampling times t_1 and t_2. Reprinted with permission after Miller et al.[55]

I - $T>T_I$

II - $T<T_I$



1 $\tau_M=1/\gamma_{nM}(M-m)$

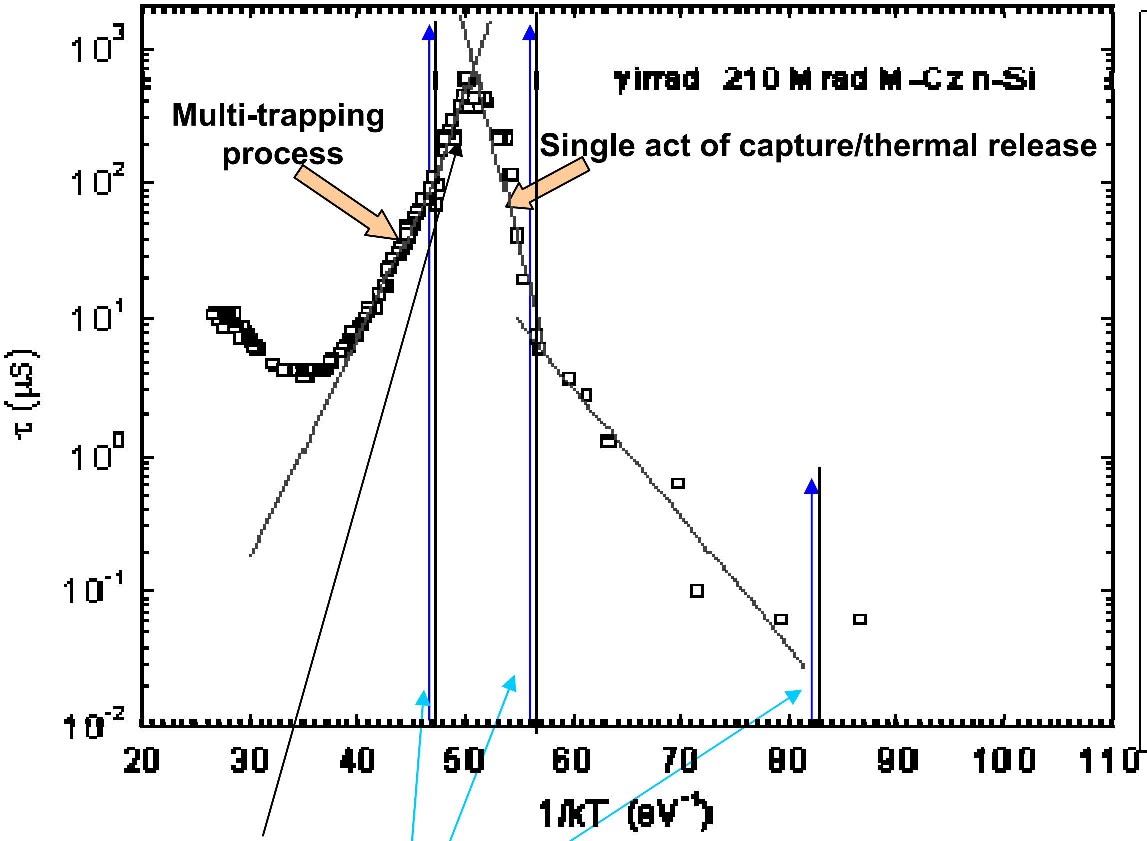
2 $\tau_N=1/\gamma_{nM}N_{CM}$

$\Theta_I = 1/[\gamma_{nM}N_{CM} + \gamma_{nM}(M-m)]$

$\Theta_{II} = 1/[\gamma_{nM}N_{CM}]$

Precise simulation of the temperature dependent lifetime variations correlating with DLTS peaks – J.Vaitkus' method

Using ratio Θ_{II}/τ_{asymp} *an activation energy* E_M *of* γ_{nM} or τ_R , or combinations of γ_{nM} , n_0 , τ_R and N_{CM} *parameters can be extracted*

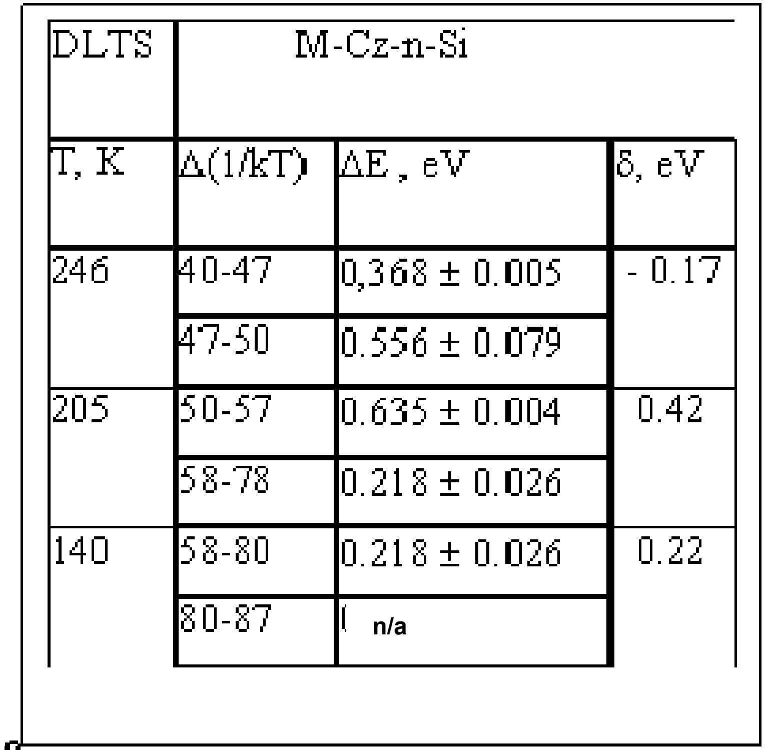


Multi-trapping process

Single act of capture/thermal release

MWR decay τ_{as} peak

Common DLTS peaks



DLTS	M-Cz-n-Si		
T, K	Δ(1/kT)	ΔE , eV	δ, eV
246	40-47	0,368 ± 0.005	- 0.17
	47-50	0.556 ± 0.079	
205	50-57	0.635 ± 0.004	0.42
	58-78	0.218 ± 0.026	
140	58-80	0.218 ± 0.026	0.22
	80-87	(n/a	

Summary

☼ MWR instrumentation and regimes are tested, models adjusted, software for analysis made up.

☼ tentative examination of recombination characteristics dependent on fluence and particle species, by MWR using $\tau(T)$, $I_{exc,}$ $\lambda_{exc,}$ BI are carried out; $\tau_{as}(T)$ variations are correlated with those determined by DLTS technique.

☼ activation factors of trapping (release) centers E_1 =0.14 - 0.16 eV, E_2 =0.23 eV and E_3=0.48 eV, have been evaluated in e-irradiated FZ Si diode from carrier lifetime variations with temperature in the range of 140 →350 K. These trap activation energy values, measured by MWR using $\tau(T)$, are in agreement with those determined by DLTS technique.

☼ in γ-rays irradiated MCZ Si, the activation energy values of trapping and recombination (E_M *and* E_R) centers were obtained as follows: E_1 =0.14 eV, E_2 =0.28 - 0.30 eV, E_3=0.38 eV, and E_4=0.48 – 0.56 eV, by MWA using $\tau(T)$.

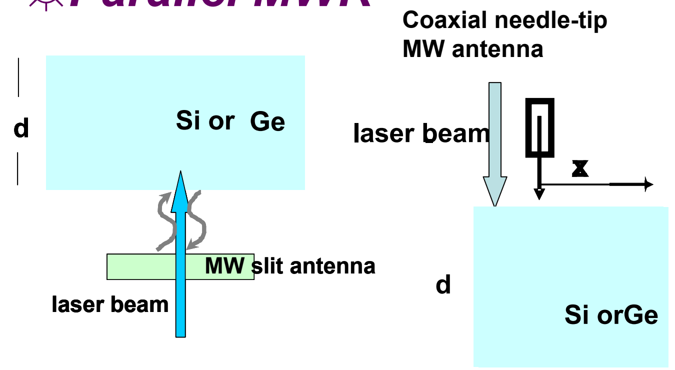
☼ Correlating DLTS and MWR transients, additional information about the centre can be extracted concerning the type of the center, capture barrier etc

Thank You for attention!

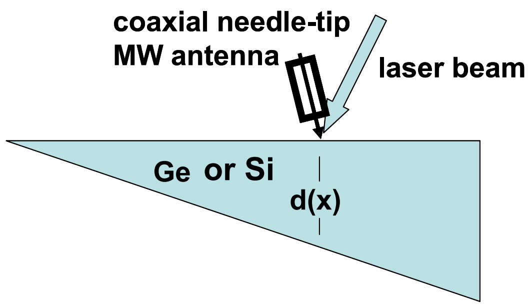
Perspective development of the MW techniques for:

- estimation of carrier transport parameters

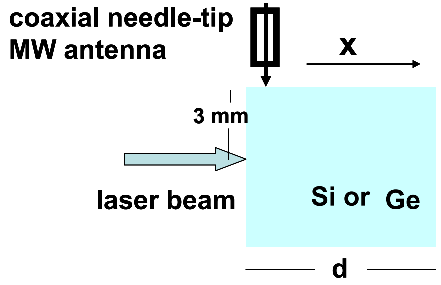
☼Parallel MWR

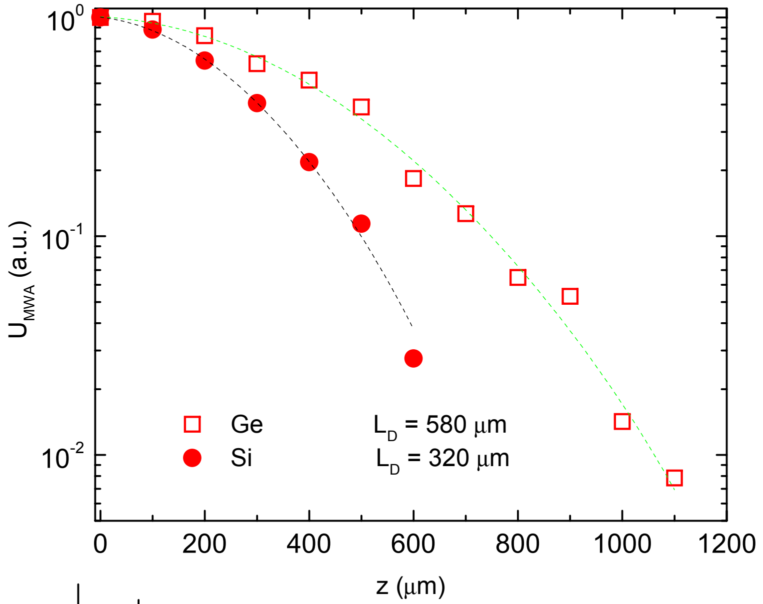


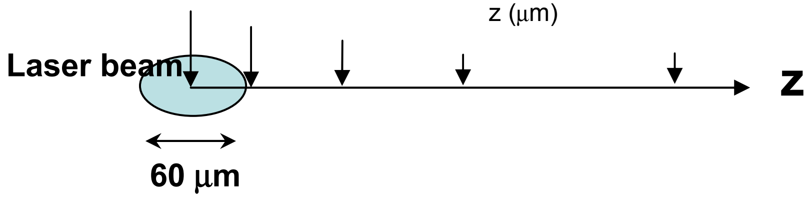
☼Oblique MWR

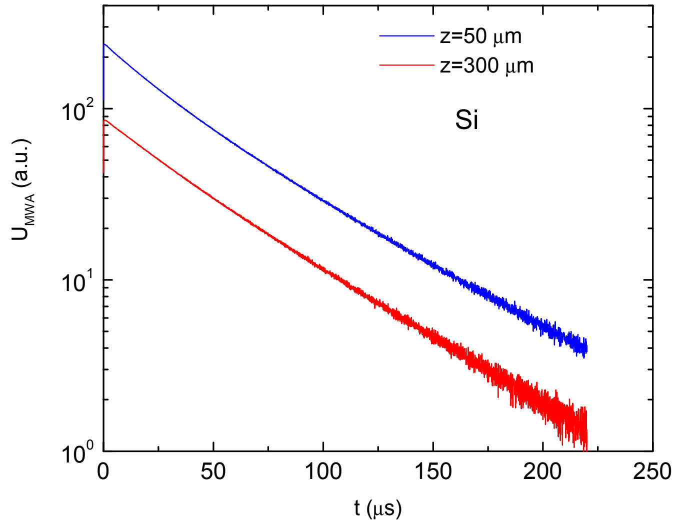


☼ Perpendicular MWR









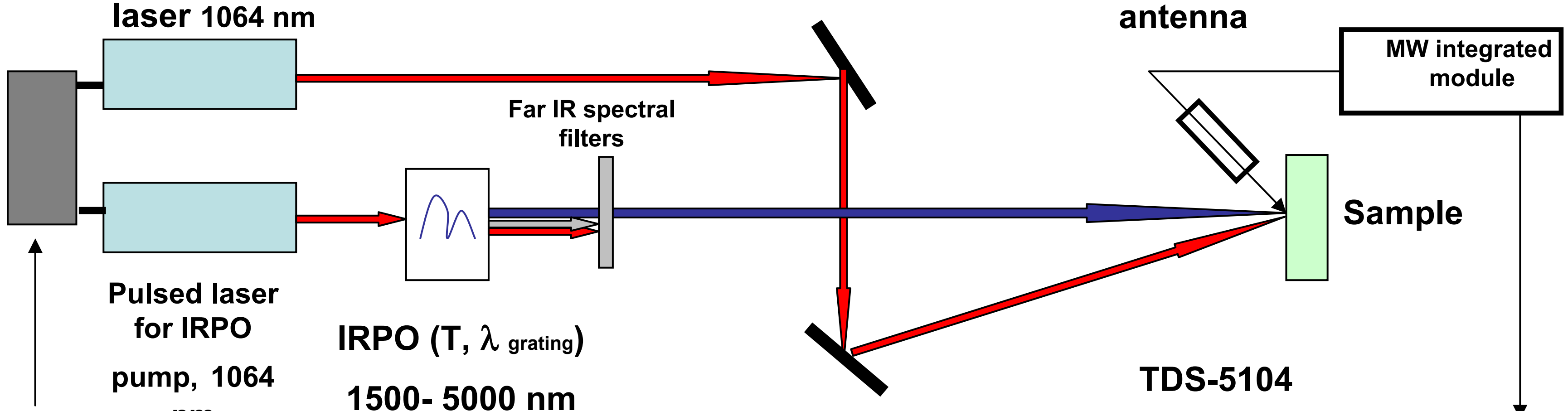
$$L_{\min} = \sqrt{D_{\min}\tau_R}$$

$D \approx 67$ cm^2/s p-Ge

$D \approx 21$ cm^2/s p-Si

Perspective development of the MW techniques for:

- estimation of trap spectral parameters



Excitation pulsed IR laser 1064 nm

Coaxial needle-tip MW antenna

MW integrated module

Far IR spectral filters

Sample

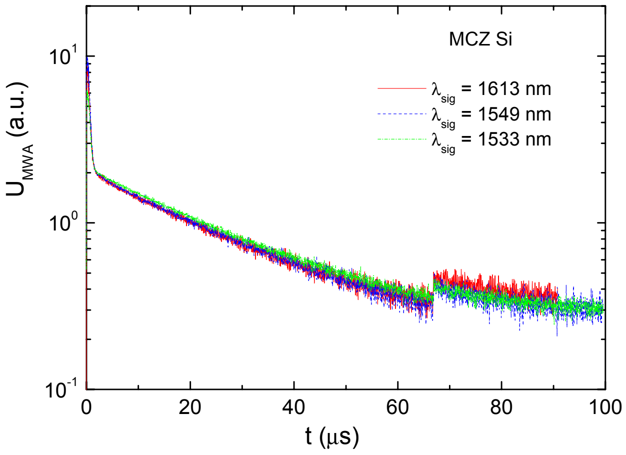
Pulsed laser for IRPO pump, 1064 nm

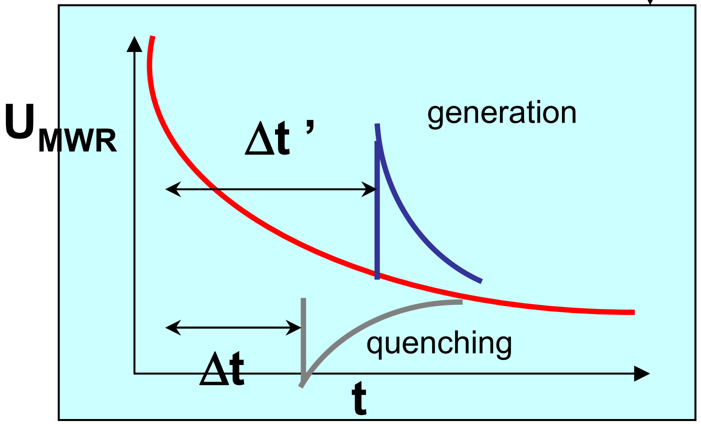
IRPO (T, λ_{grating})

1500- 5000 nm

Electronic pulse timing & shift (Δt) system

TDS-5104





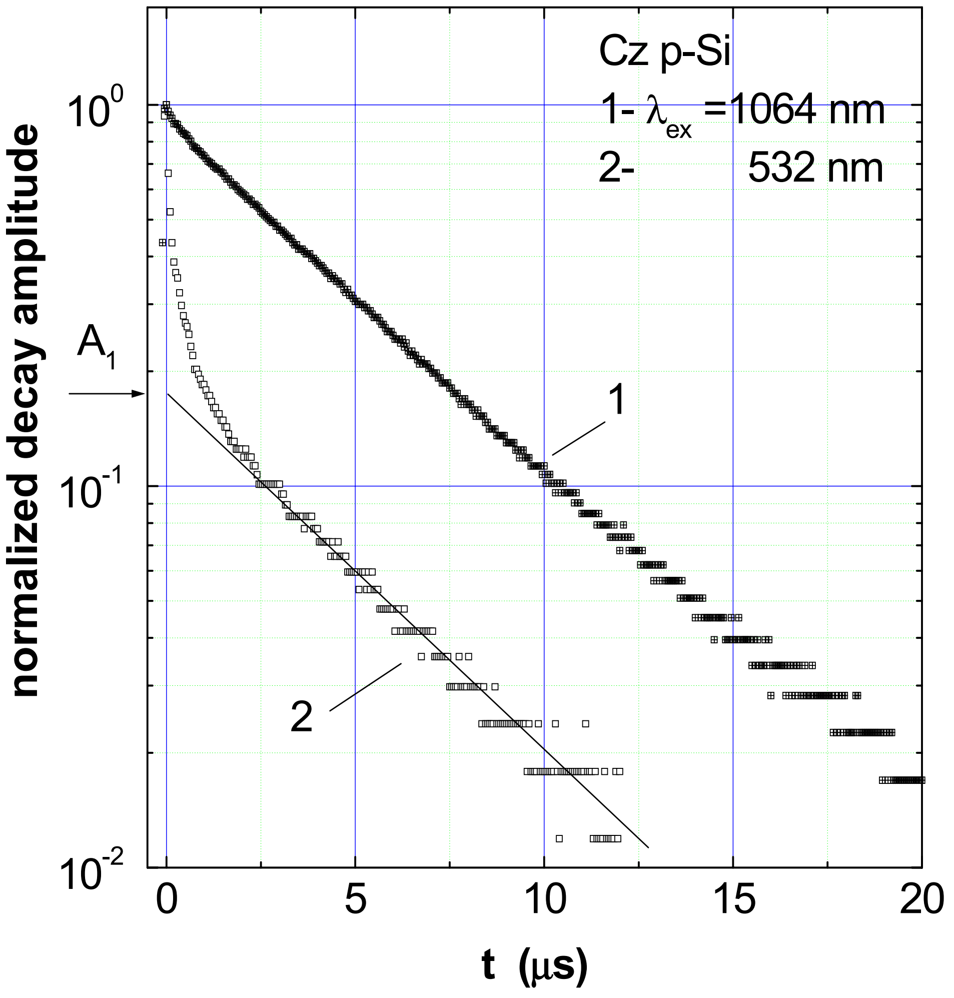
Carrier recombination in the bulk and at surface

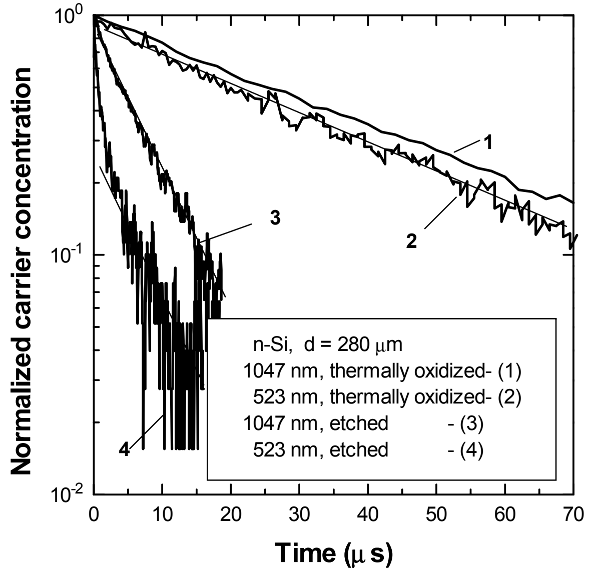
☼ *Transitional and main decay mode constituents within transients.*

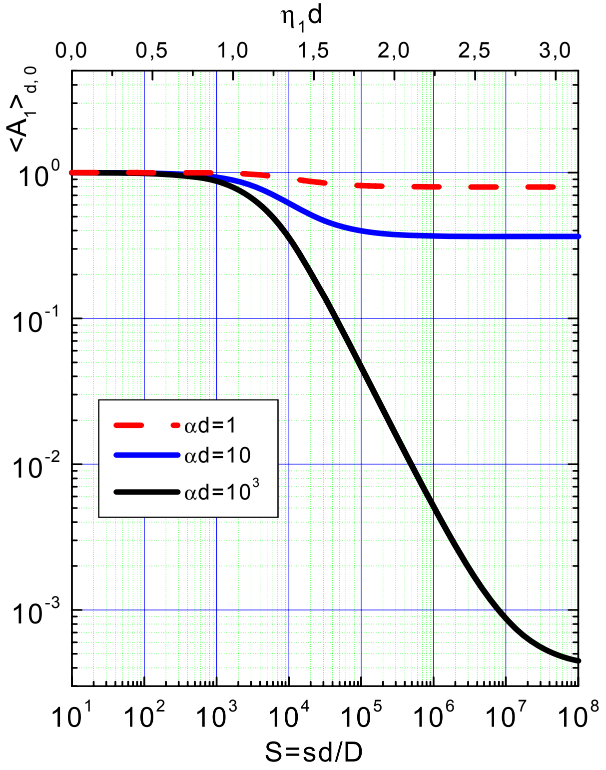
Surface and bulk recombination parameters can be separated

by varying excitation domain.

$$\frac{<n(t)>_d}{<n(0)>_d} = \sum_{m=1}^{\infty} A_m(\eta_m d, \alpha d)\, e^{-\frac{t}{\tau_m}}\, e^{-\frac{t}{\tau_b}}$$







Carrier decay/trapping parameters

DLTS

$e \sim 1/\tau_e = \sigma v N_{C,Vm} = e^{|Ec,v-Em|/kT} / \sigma v N_{C,V}$

MWR

$\tau_{as} \sim \tau_e = 1/\sigma v N_{C,Vm} = e^{|Ec,v-Em|/kT} / \sigma v N_{C,V}$

I-V n⁺p junction *- according to D.Schroder Sol.St.Phen. v.6&7 (1989) 383*

$$\mathbf{I_F \sim I_{diff} = I_{sat} (e^{qV/kT}-1) = qAN_cN_v e^{-Eg/kT}[\, D_p e^{\Delta Eg/kT}/N_D L_{peff} + D_n/N_A L_{neff}]\, (e^{qV/kT}-1)}$$

$\mathbf{L_{n,p\ eff}} = L_{n,p}\,[1+(s_r L_{n,p}/D_{n,p})\tanh(d/L_{n,p})]/[(s_r L_{n,p}/D_{n,p}+\tanh(d/L_{n,p})]\big|_{d<Ln} \approx \mathbf{d[(s_r+D_n/d)/(s_r+d/\tau_R)];}$

$L_{n,p} = (D_{n,p}\tau_R)^{1/2}$

MWR $\tau \sim \tau_R$ *–monoexp*; $s_r \leftarrow A_{1,}\ \tau_{Reff\ ,}$ 2-compon.

$I_{Rev} \rightarrow I_{rev}(scr) + I_{rev}(qnr) = qn_iWA/\tau_{geff} + \mathbf{qAN_cN_v e^{-Eg/kT}[\, D_p e^{\Delta Eg/kT}/N_D L_{peff} + D_n/N_A L_{neff}]}$

$\tau_{geff} = \tau_g/(1+2s_g\,\tau_g/r)$ $I_{Rev}\,|_{FD} \approx qn_iWA/\tau_{geff}$

MWR $\tau_{as} \sim \tau_e + \tau_{tr}$