Carrier recombination and emission lifetimes in heavily irradiated pad–detectors and their impact on operational characteristics of pin diodes

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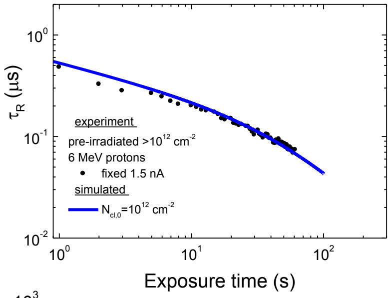
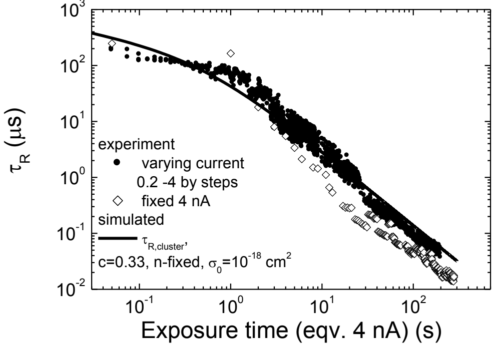
Outline

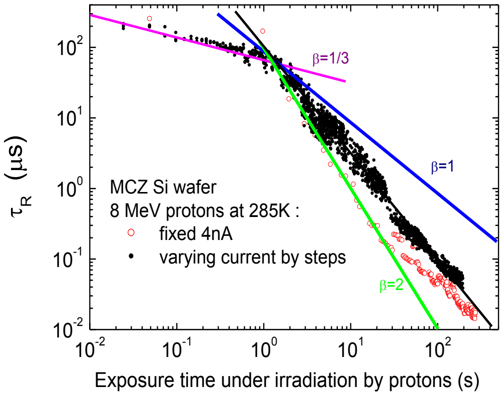
- Carrier capture (MW-PCD/E) and emission (I-V) lifetime variations
- Barrier capacitance variations with fluence (BELIV)
- Time and spectral resolved priming of BELIV transients
- Summary

Recombination lifetime during and after irradiation

During protons irradiation/ protons pre-irradiated (MW-PCD) - wafer samples



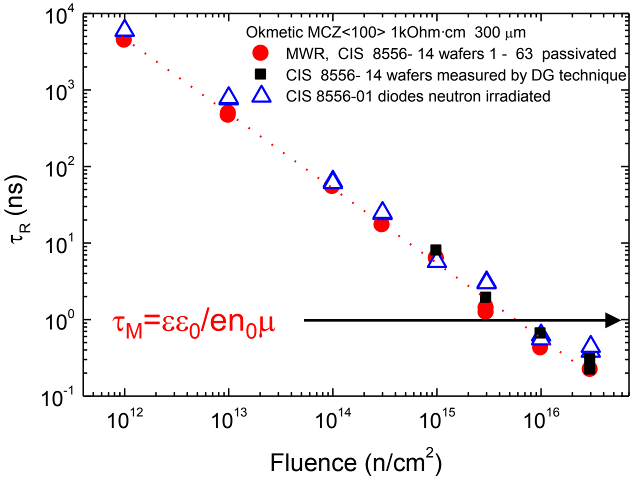


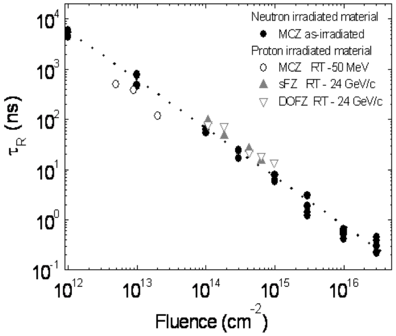


recombination prevails

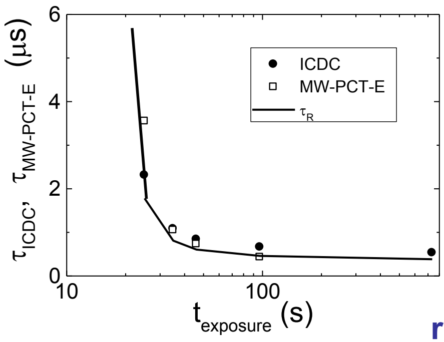
After irradiation - wafer and diode samples irradiated by neutrons and protons

$\Delta n<n_0$





- diode samples with applied field

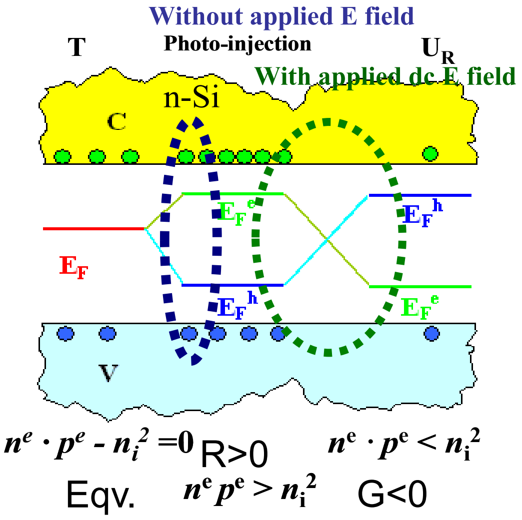


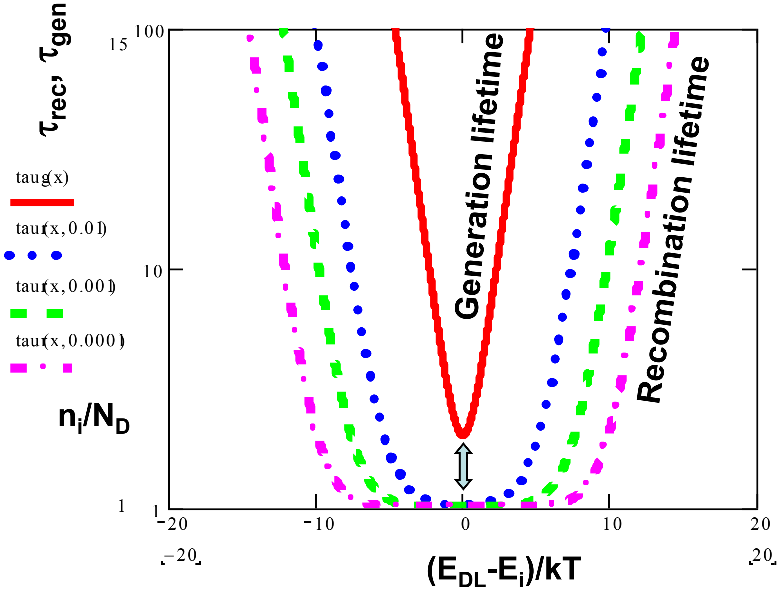
$\Delta n<n_i<<n_0$

recombination competes with multi-trapping effect

Impact of recombination within ENR with $\tau_R\leq\tau_M$ might be crucial (if n_0~$1/\Phi$) on functionality of junction

Carrier capture-recombination-generation lifetimes (simple S-R-H approach)

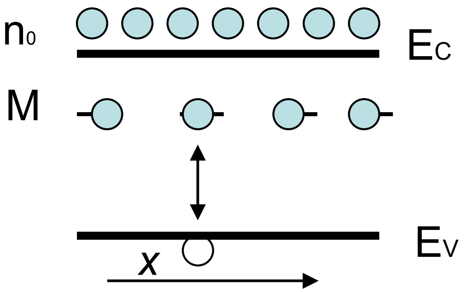




$$\tau_{rec} = \frac{\Delta n}{R} = \frac{1}{v\sigma N_{DL}}\left[1 + \frac{2n_i}{n^e}\cosh\left(\frac{E_{DL}-E_i}{kT}\right)\right]$$

$$\tau_{gen} = n_i / G = \frac{2\cosh\left(\frac{E_{DL}-E_i}{kT}\right)}{v\sigma N_{DL}}$$

at $\sigma_n v_n \cong \sigma_p v_p$



Single-type prevailing traps of $M = N_{DL} << n_0$

Traps with barriers, multitrapping
multi-charge/multi-valency defects

J.S. Blakemore, in: *Semiconductor Statistics, Ch. 8,* Pergamon Press, (1962)

Traps with exp distributed levels
Redistribution of carriers via interaction of traps
Photo-, thermo- quenching effects

A.Rose. Concepts in photoconductivity and allied problems.
Interscience Publishers, John Wiley & Sons, New York-London, 1963.

S-R-H is limited by conditions:
- **i) $M << n_0$. then traps are filled by δn_0 without change in n_0;**
- **ii) single type centers dominate**
- **iii) traps do not interact**
- **iv) charge on traps can be ignored relatively to dopants one**

Thus, validity of S-R-H conditions should be estimated in applications

Carrier recombination lifetimes (for M>>n_0)

Single-species (type) traps

$$\tau_p = \frac{\tau_{n0}(P_0 + P_{vM}) + \tau_{p0}\left[n_0 + N_{cM} + M\left(1 + \frac{n_0}{N_{cM}}\right)^{-1}\right]}{p_0 + n_0 + M\left(1 + \frac{n_0}{N_{cM}}\right)^{-1}\left(1 + \frac{N_{cM}}{n_0}\right)^{-1}}$$

$$\tau_n = \frac{\tau_{p0}(n_0 + N_{cM}) + \tau_{n0}\left[p_0 + P_{vM} + M\left(1 + \frac{p_0}{P_{vM}}\right)^{-1}\right]}{p_0 + n_0 + M\left(1 + \frac{p_0}{P_{vM}}\right)^{-1}\left(1 + \frac{P_{vM}}{p_0}\right)^{-1}}$$

$$m_0 = \frac{M}{e^{\frac{-\Delta \mathrm{E}_M - F}{kT}} + 1} = \frac{M}{\frac{N_{cM}}{n_0} + 1} = M - \frac{M}{\frac{P_{vM}}{p_0} + 1}$$

Although relaxation to equilibrium/steady-state is kept by M=p_M+n_M

M→0, Δn →0, S-R-H

$$\tau = \tau_p = \tau_n = \tau_{p0}\frac{n_0 + N_{cM}}{n_0 + p_0} + \tau_{n0}\frac{p_0 + P_{vM}}{n_0 + p_0}$$

Capture coefficient <γ_n> should be used instead of vσ within rigorous analysis

$$r = n\langle\gamma_n\rangle N_f P_h\left(E_f\right)$$

$$r = N_f P_h\left(E_f\right)\int_{E_c}^{\infty}\gamma(E)P_e(E)g_c(E)dE$$

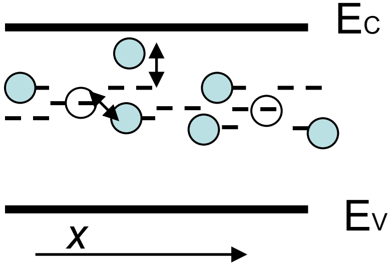
$$\langle\gamma_n\rangle = \frac{\int_{E_c}^{\infty}\gamma(E)P_e(E)g_c(E)dE}{\int_{E_c}^{\infty}P_e(E)g_c(E)dE}$$

J.S. Blakemore, in: *Semiconductor Statistics, Ch. 8,* Pergamon Press, (1962)

M→∞, M>>n_0, S-R-H invalid

$$\tau_p = \tau_{p0}\left(1 + \frac{N_{cM}}{n_0}\right) = \frac{1}{\gamma_p m_0} = \tau_{p0}$$

$$\tau_n = \tau_{n0}\left(1 + \frac{P_{vM}}{p_0}\right) = \frac{1}{\gamma_n(M - m_0)} = \tau_{n0} = \frac{1}{\gamma_n M}$$



$$\boxed{\tau_n \neq \tau_p}$$

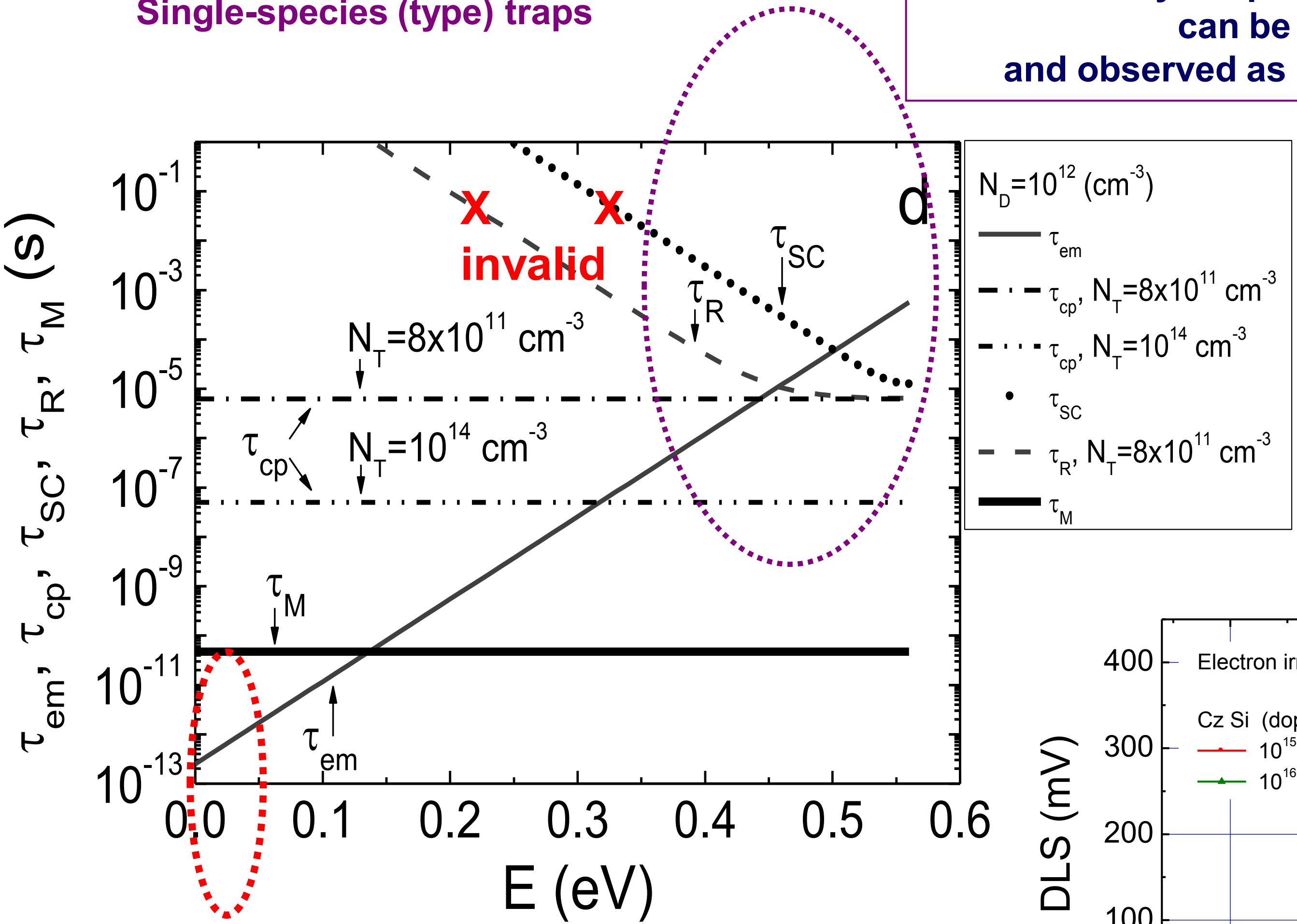
$$\boxed{\tau_{rec} = \frac{1}{v\sigma M} = \frac{1}{<\gamma_n> M}}$$

$$\boxed{\tau_{gen} = \frac{\exp(\frac{E_C - E_M}{kT})}{v\sigma N_C} = \frac{\exp(\frac{E_C - E_M}{kT})}{<\gamma> N_C}}$$

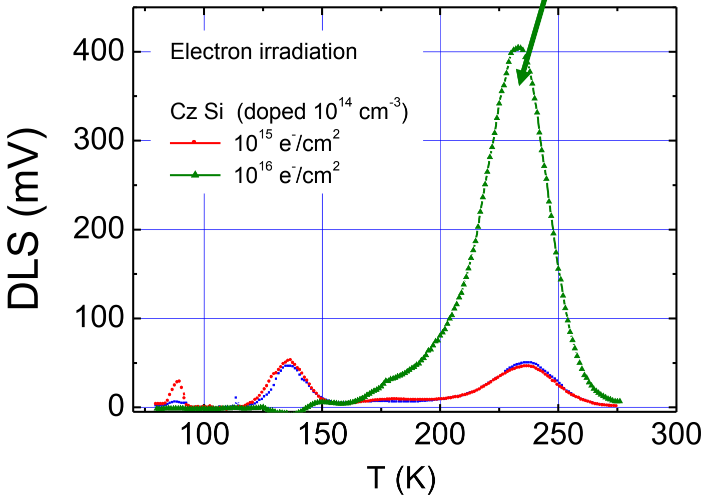
Carrier recombination=capture lifetimes (for M>>n_0)

Single-species (type) traps

Only deep slow levels can be filled and observed as carrier emitters



Space charge generation current



Only shallow dopants of proper density are able to support fast operation (w(U_ω)) of a diode $\omega \sim 1/\tau_M < 1/\tau_{em}$

to ensure maj. carriers on level are in equilibrium with band

Interaction of several type centers appears due to carrier redistribution through bands

Carrier recombination lifetimes for $M_{i,s}>n_0$ multi-valency(i)/multi-species(s) centers

Interaction of the whole system of centers appears due to carrier redistribution through bands, by inter-center recombination (capture-emission) and via charging /configurational transforms of defects

System neutrality is supported by free and localized charges/fields.
Relaxation is long and complicated.
It is similar to the random-walk processes in disordered materials.

S.Havlin and D.Ben-Avraham, Advances in physics **51, 187** (2002).
L.Pavesi, J. Appl. Phys. **80, 216 (1996).**

The stretched-exponent model is widely used $U_{CPC} = U_0 \exp[-(t/\tau_{se})^{\alpha}]$

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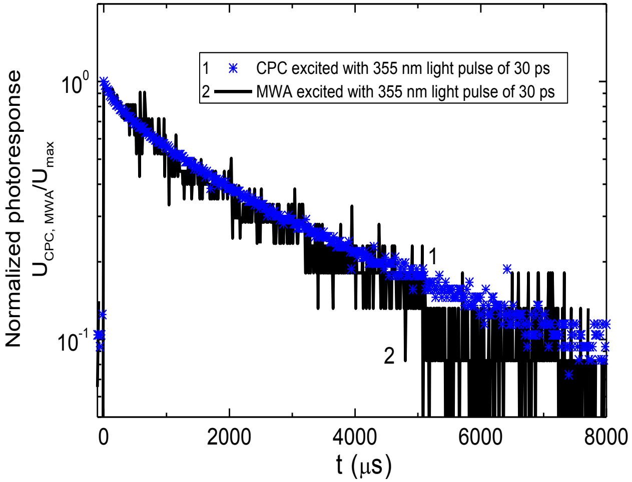
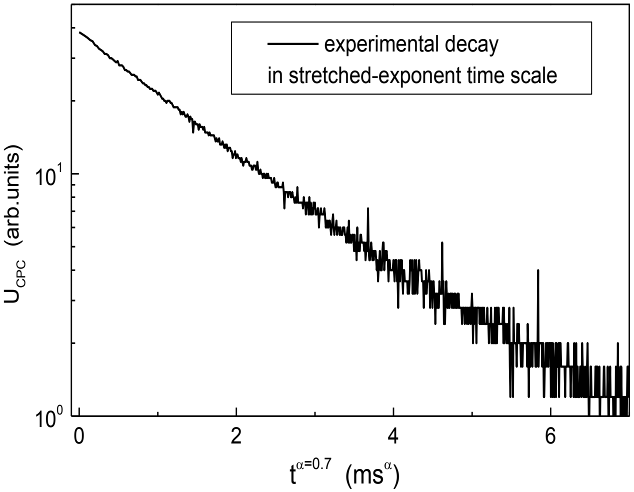


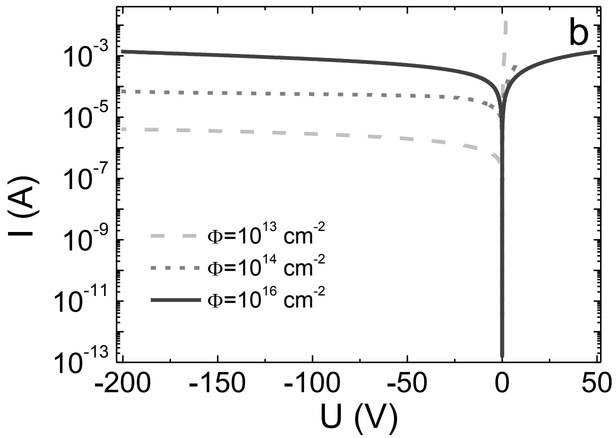


Relaxation is similar to multi-exponential in any narrow display segment

Different techniques may give different lifetime values

A single lifetime parameter τ_{se} can be extracted only when stretched-exponent time scale is employed

Carrier generation/emission lifetime (for $M>>n_0$)



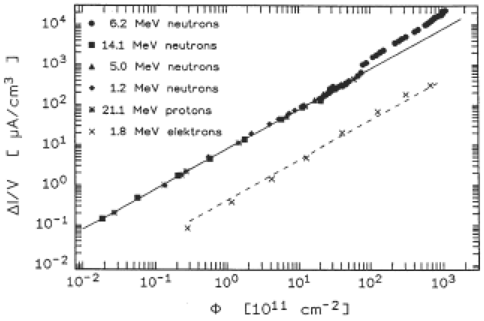
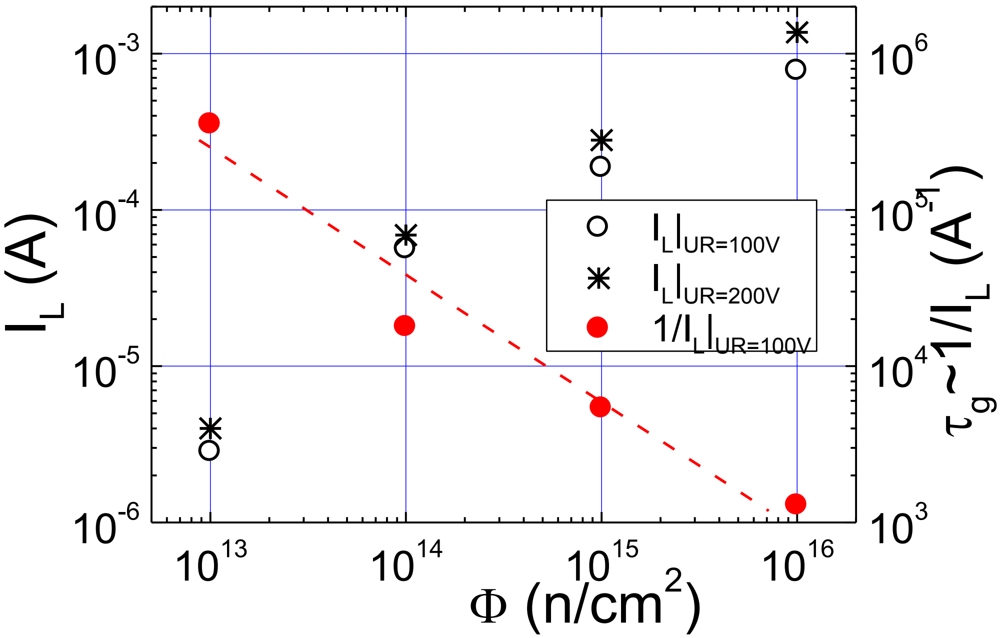
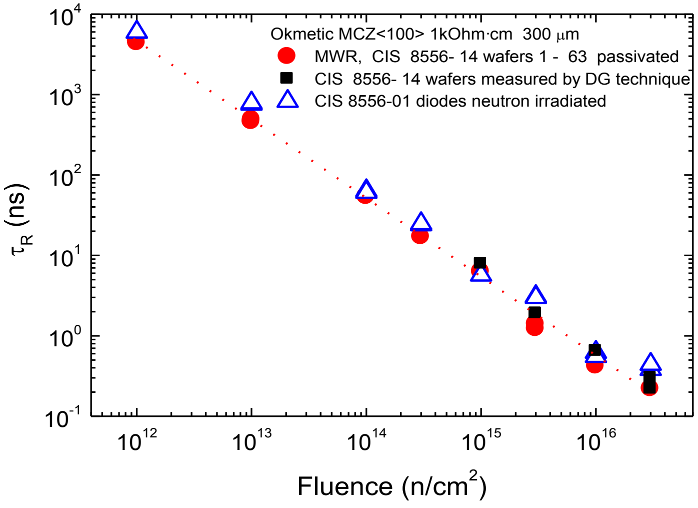


Fig. 11.11. A 1 MeV neutron equivalent fluence dependence and parameterization of the volume-generated current for an n-type silicon wafer irradiated with neutrons. The data have been corrected for self-annealing occurring during the extended irradiation period. For neutrons, straight lines with $\alpha = 8.0 \times 10^{-17}$ A cm^{-1} and for electrons $\alpha_e = 4.2 \times 10^{-18}$ A cm^{-1} have been plotted in double-logarithmic form. (After Wunstorf 1992a, Fig. 5.14)



Qualitative emission lifetime dependence on fluence can be estimated from I-V



Nearly linear reduction of generation lifetime with enhancement of fluence is similar to that of of recombination lifetime characteristic

- **Examined MW-PCT characteristics imply prevailing of intricate system of defects and reduction of majority carriers. The recombination capture lifetimes become shorter than dielectric relaxation time.**

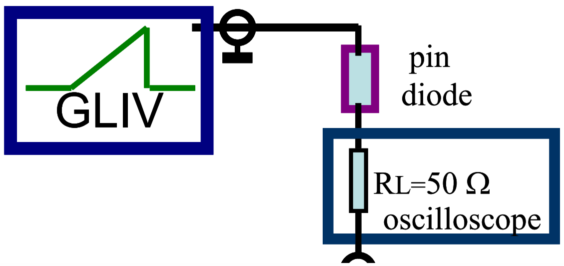
- **Carrier emission lifetime decrease (increase of leakage current – at U_R in I-V), follows capture lifetime reduction (increase of serial resistance $R\sim1/n_0$ - at U_F in I-V), and both manifest a close to a linear decrease with enhancement of fluence**

Items to clarify:

- **Whether diode/detector is functional under heavy irradiations?**
- **What is a system of defects and levels, which governs extraction of carriers (U_R) and state of material?**
- **Which models are acceptable for prediction of charactreristics?**

The Barrier Evaluation by Linearly Increasing Voltage (BELIV) transient technique has been employed to clarify, how a reduction of carrier capture lifetime and emission affects junction and material

BELIV technique



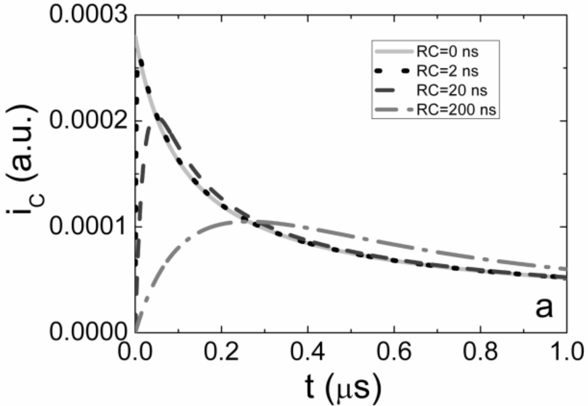
Reverse bias

$$i_C(t)=\frac{dq}{dt}=\frac{\partial U}{\partial t}(C_b+U\frac{\partial C_b}{\partial U})=AC_{b0}\frac{1+\frac{At}{2U_{bi}}}{(1+\frac{At}{U_{bi}})^{3/2}}$$

Abrupt junction

$$i_{C,Lg}=AC_{b0,Lg}\frac{[1+\frac{2}{3}\frac{At}{Ubi,Lg}]}{[1+\frac{At}{Ubi,Lg}]^{4/3}}$$

Linearly grade junction

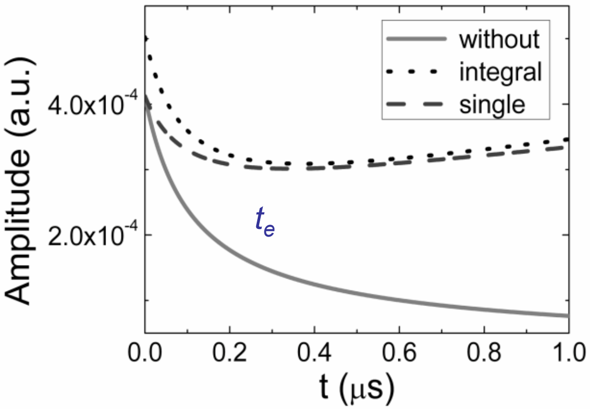


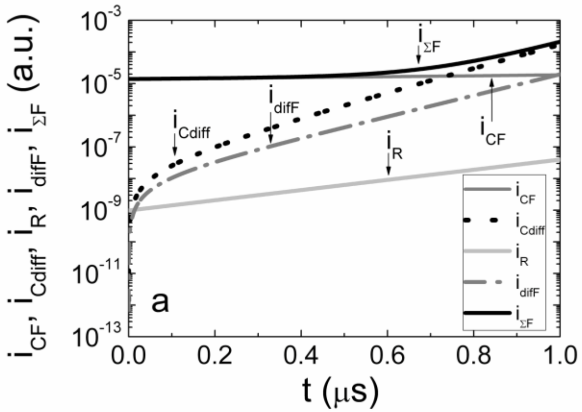
$$i_{R\Sigma}(t)=i_C(t)+i_{diff}(t)+i_g(t)=AC_{b0}\frac{1+\frac{At}{2U_{bi}}}{(1+\frac{At}{U_{bi}})^{3/2}}+i_{diff\infty}(1-e^{-\frac{eAt}{k_BT}})+\frac{en_iSw_0}{\tau_g}(1+\frac{At}{U_{bi}})^{1/2}$$

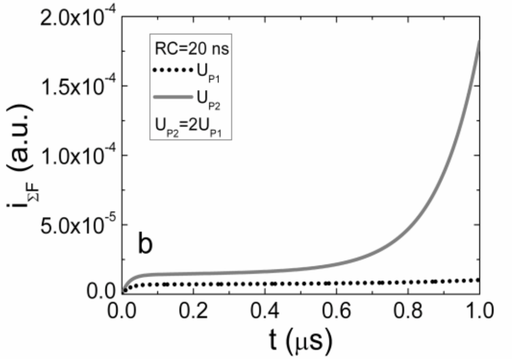
$$t_e=\frac{U_{bi}}{Ai_g(0)}[\frac{i_C(0)}{4}-i_g(0)+\sqrt{(\frac{i_c(0)}{4})^2+\frac{3}{2}i_c(0)i_g(0)}]$$

$$i_{CM}(t)=\frac{1}{\tau_{RC}}\int_0^t i_C(x)\exp[-\frac{(t-x)}{\tau_{RC}}]dx$$

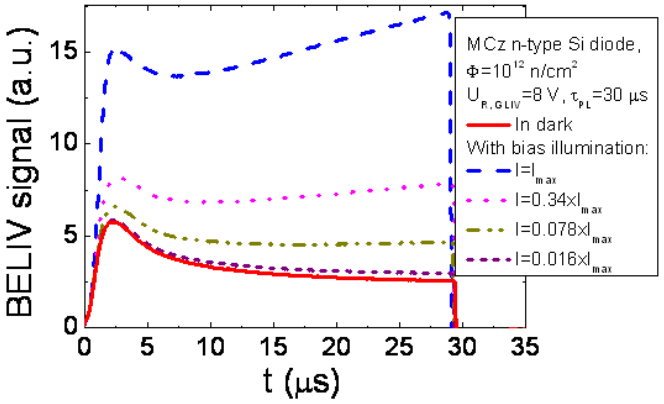
$$|i(t)|_{FD}=eS\frac{d}{2}(\frac{dn}{dt}+\frac{dp}{dt})+\frac{\varepsilon\varepsilon_0 S}{d}\frac{dU_C}{dt}\approx eS\frac{d}{2}\frac{n_0}{\tau_{tr}}+C_{geom}\frac{dU_C}{dt}=e\frac{S}{2d}n_0\mu_nU_C(t)+C_{geom}\frac{dU_C(t)}{dt}$$



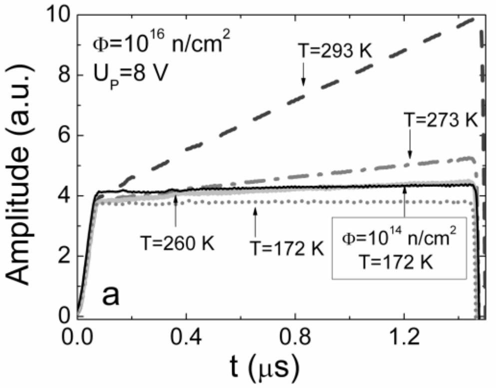




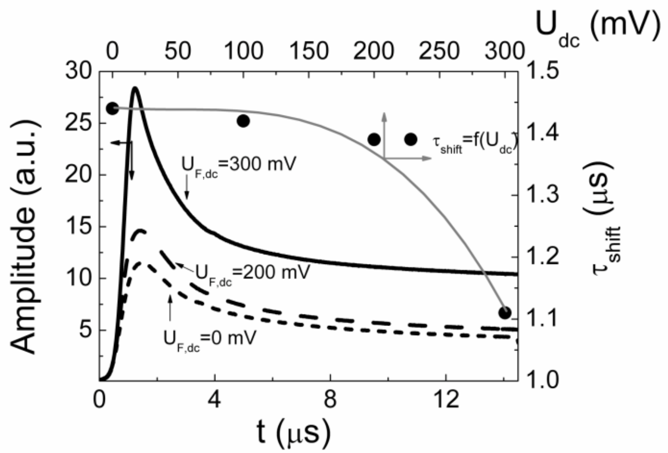
Variations of BELIV transients with temperature and priming by steady-state IRBI as well as dc U



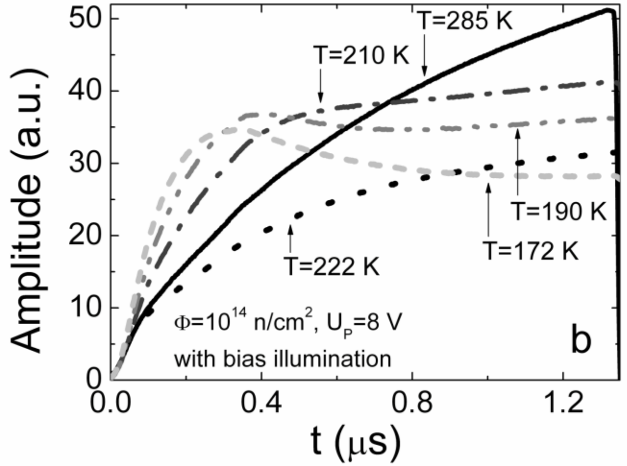
Priming by IR illumination increases n_0 *and* barrier capacitance observed in BELIV transients restores a junction but enhances leakage current when fast carrier capture/emission is present



Reduction of temperature increases (τ_e) and decreases space charge generation current, however, $C_{b0}≅C_g$ at U_C<0.3 V

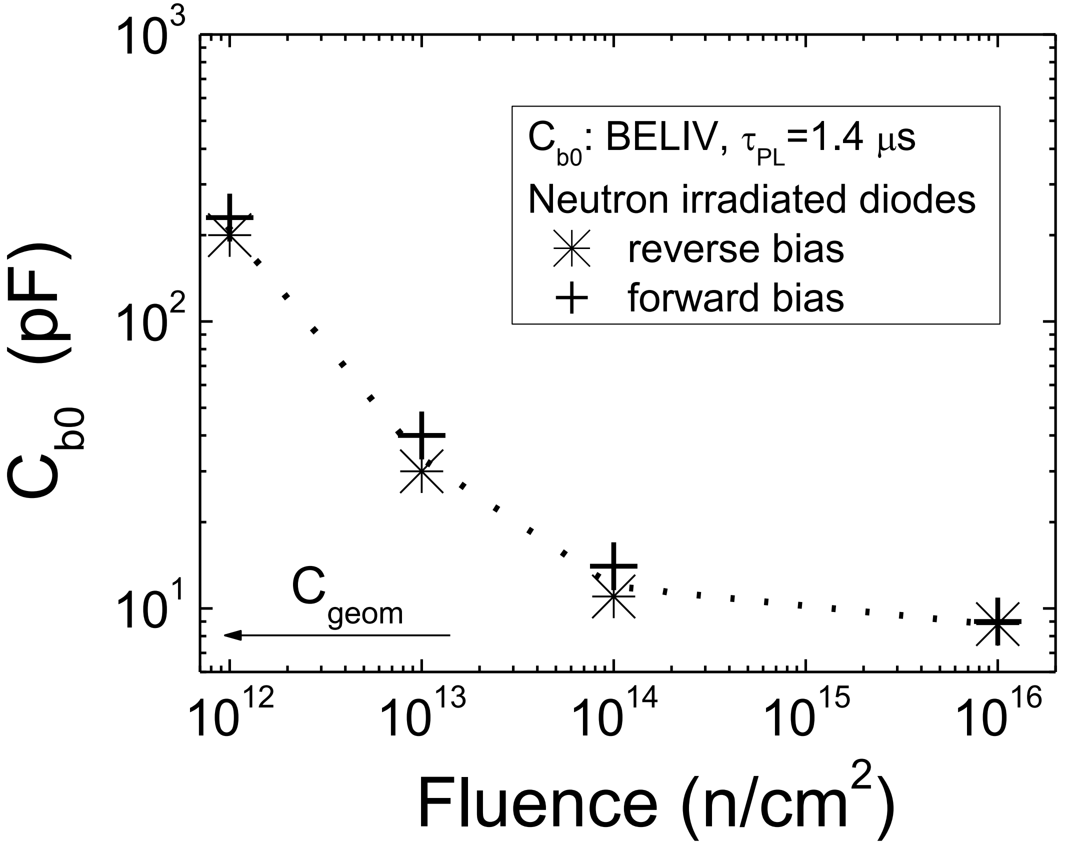


Short carrier capture lifetime reduces $n_0≅N_D$ and increases a serial resistance of ENR. Supply of majority carriers from rear electrode by dc U_F priming (due to shrinkage of depletion *w* width, forward current) restores a junction.



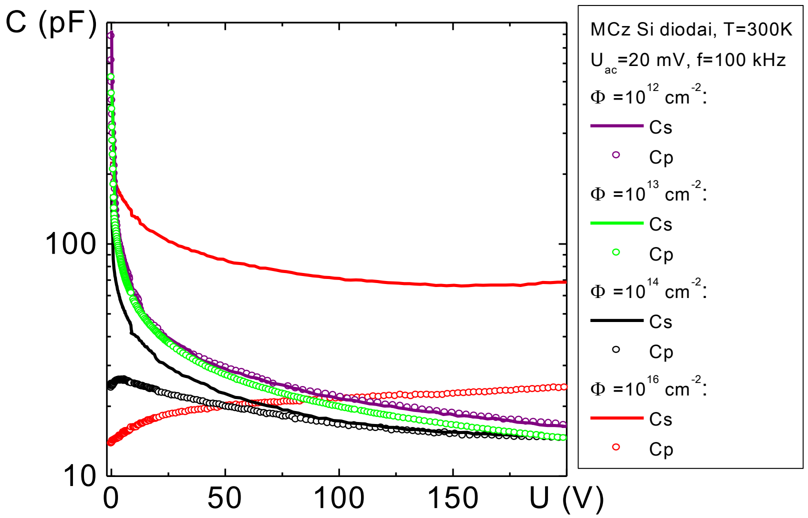
Combined priming of BELIV transients by temperature reducing *(increased τ_e)* and by IR illumination *(n_0)* leads to restore of a junction

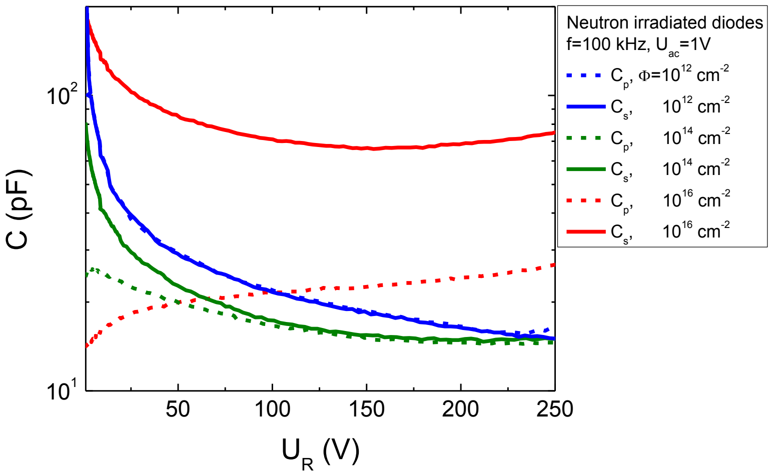
Barrier capacitance as a function of fluence extracted at 300 K



C-V's as a function of fluence at 100 kHz and 300 K

displacement in barrier capacitance is controlled by (LRC) measurements of phase shift for the ac test signal at fixed frequency in routine C-V





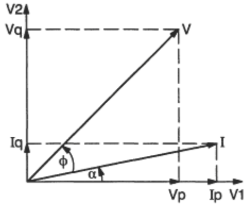
Applicability of LRC measured C-V is doubtful for diodes irradiated with > 1E13 n/cm2

1. **Reference measurement**

At the beginning of each measurement cycle, a reference measurement is performed. The measured value serves as reference for the subsequent four measurements.

2. **Voltage measurement: 0°**
3. **Voltage measurement: 90°**
4. **Current measurement: 0°**
5. **Current measurement: 90°**

The following phase diagrams and formulas show the mathematic basics for internal calculation of the component value.



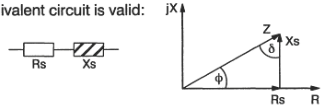
V: voltage
I: current
V1, V2: 0°-voltage, 90°-voltage

The phase angle between I and V is ϕ.
The phase angle between I and V1 is α.

In the diagram the phase relation between I and V happens to be a lossy inductance.
In each measurement cycle, the following components are determined:
Vp, Vq, Ip, Iq.
The series resistance and reactance are calculated from these components.

$$\boxed{Rs = \frac{VpIp + VqIq}{Ip^2 + Iq^2}} \quad (1) \qquad \boxed{Xs = \frac{VqIp + VpIq}{Ip^2 + Iq^2}} \quad (2)$$

The following equivalent circuit is valid:



Quality factor: $Q = \tan\phi = 1/D = \frac{|Xs|}{Rs}$ (3)

Dissipation factor: $D = \tan\delta = 1/Q = \frac{|Rs|}{Xs}$ (4)

The magnitude of Q and the sign of Xs determine which parameter of the component is dominant.

Xs positive = inductive
Xs negative = capacitive

The formulas for the various parameters are as follows:

$Q = \frac{|Xs|}{Rs}$ see equation (3)

$Z = \sqrt{Rs^2 + Xs^2}$

$D = \frac{1}{Q}$

$Cp = \frac{1}{\omega(1 + 1/Q^2)|Xs|}$ if Xs < 0

$Rp = (1 + Q^2) \times Rs$

$Lp = \frac{(1 + 1/Q^2)|Xs|}{\omega}$ if Xs > 0

Rs see equation (1)

$Cs = \frac{1}{\omega|Xs|}$ if Xs < 0

$Ls = \frac{|Xs|}{\omega}$ if Xs > 0

Impedance $Z = R + jX$
Admittance $Y = 1/Z$

- Barrier partially recovers by n_0 priming with IR, dc UF and combined priming with temperature (emission lifetime) decreasing only in diodes irradiated with fluence of $<10^{14}$ n/cm^2.
- Short carrier capture and emission times determine low barrier capacitance (capability to to collect charge (transient) at fixed voltage) and large space charge generation (leakage) current in heavily irradiated diodes.
- The space charge generation current prevails in heavily irradiated diodes over barrier charging (displacement, which is controlled by measurements of phase shift for the ac test signal in routine C-V), therefore applicability of C-V technique is doubtful for control of heavily irradiated detectors.
- Carrier capture and emission lifetimes are short, and barrier capacitance decreases to geometrical its value at low ($U< U_{bi}$) applied voltage of the diodes with enhancement of fluence. Operation of a diode is similar to that of capacitor.

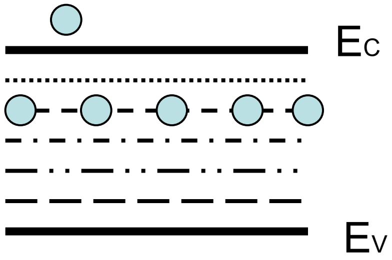
Items to clarify:

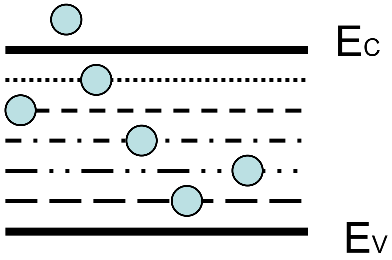
Whether diode/detector of the present design is functional after heavy irradiations?- doubtful

What is the system of defects and levels, which governs extraction of carriers (UR) and state of material?- material becomes similar to insulator.

Additonal issues: - if there are filled levels those compensate material;
- how rapidly these levels are able to response to external voltage changes

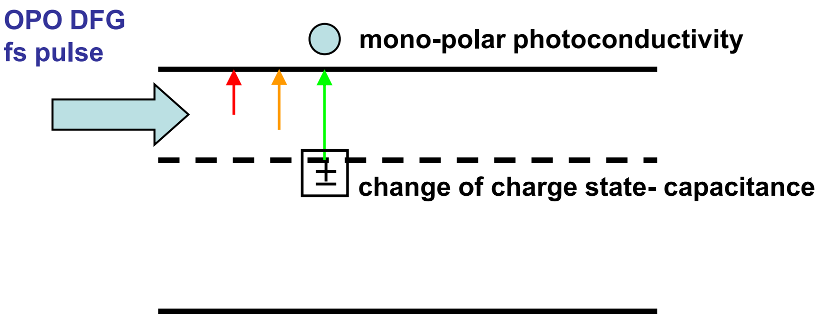
Which models are acceptable for prediction of characteristics?





The BELIV technique with spectrally resolved fs pulsed IR (1.1 – 10 µm) biasing has been employed to clarify what is a system of levels and if these levels are filled

Variations of BELIV transients by pulsed IR of varied spectrum



OPO DFG
fs pulse

mono-polar photoconductivity

change of charge state- capacitance

OPO DFG wavelength/quantum for which appears suppression of traps,
i.e. recover of BELIV transient of C_b,
indicates a system of filled single type deep levels

To approve principles
structure with known technological defects

For qualitative understanding

(within depletion approximation):

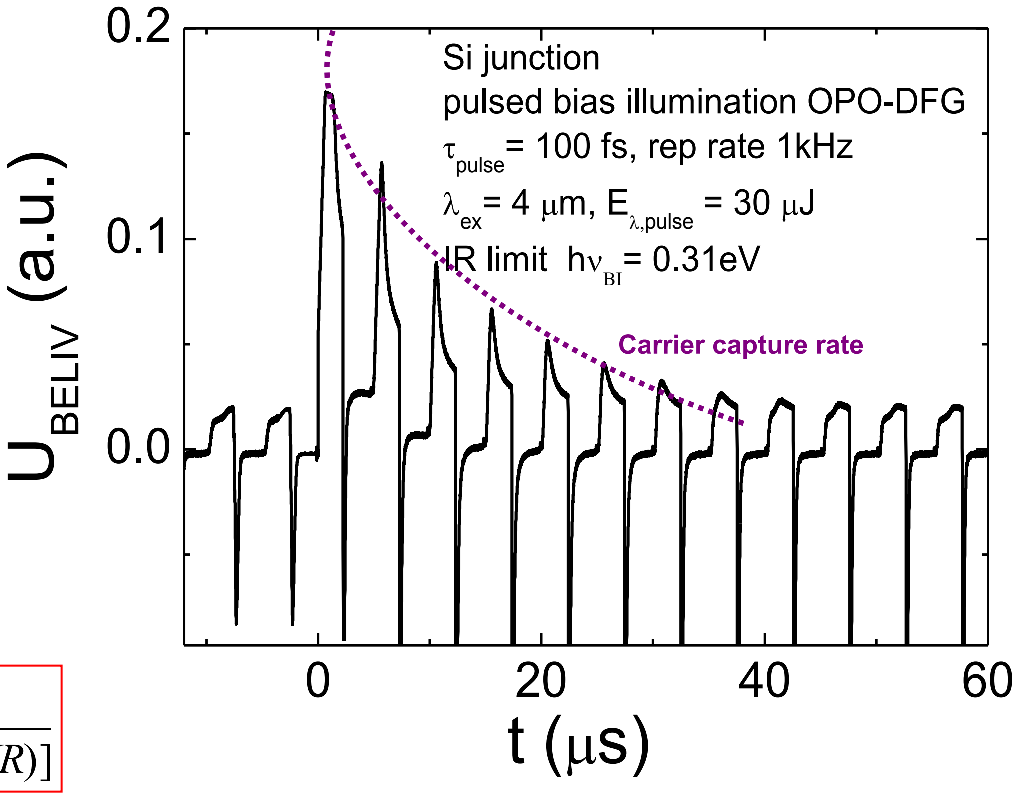
$$C_b \sim (N_D = n_0)^{1/2} \sim 1/w(n_0)$$

$$C_b(t) \sim 1/\tau_M = (e\mu n_0|_{\underset{\uparrow}{\lambda tr}})/\varepsilon\varepsilon_0$$

(using extended depletion approximation)

for transient processes

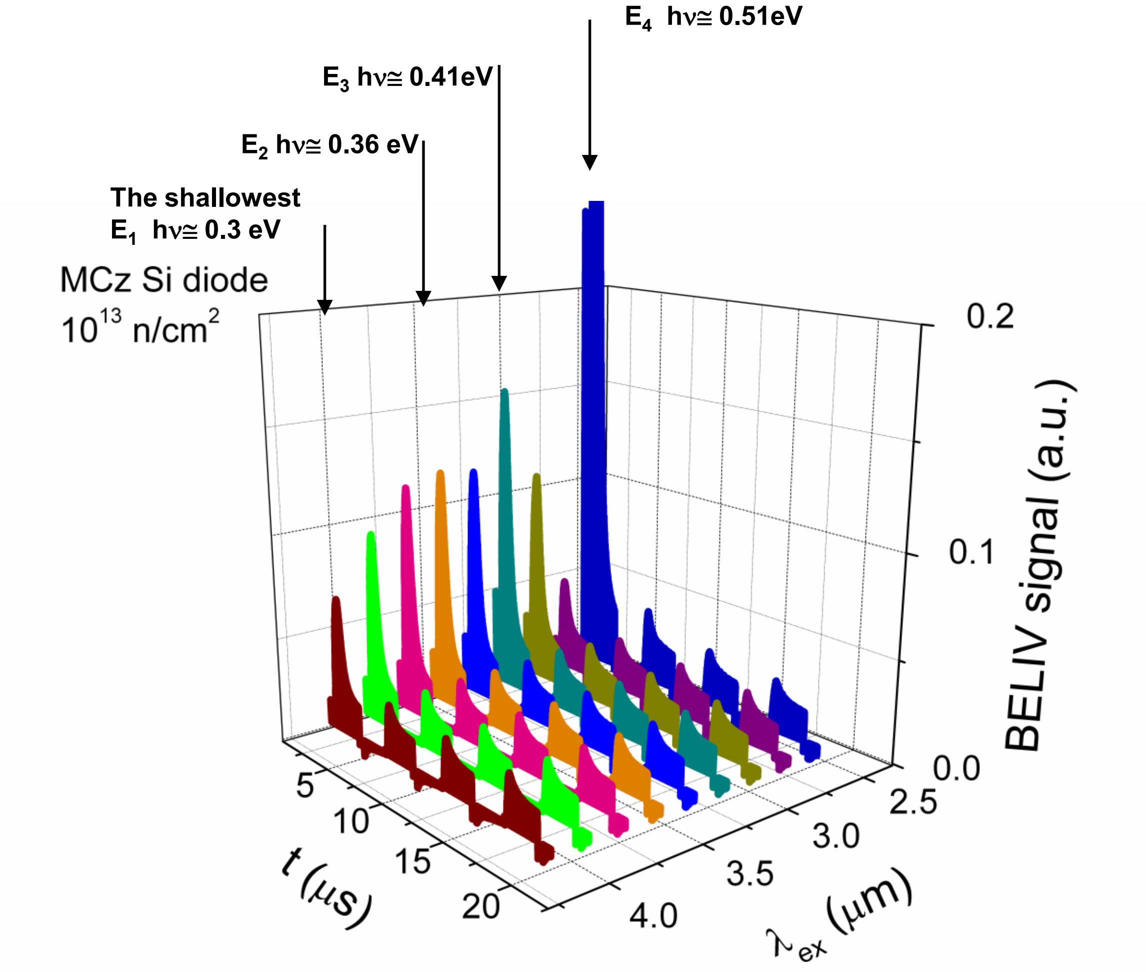
$$\boxed{\tau_M = \frac{\varepsilon\varepsilon_0}{e\mu n_0} = \frac{\tau_{dr,\lambda}}{2} = \frac{\lambda^2}{2\mu U_\lambda} = \frac{e\lambda^2}{e\mu[E_C(\lambda) - E_C(ENR)]}}$$



Si junction
pulsed bias illumination OPO-DFG
τ_{pulse}= 100 fs, rep rate 1kHz
λ_{ex}= 4 μm, $E_{\lambda,pulse}$ = 30 μJ
IR limit $h\nu_{BI}$= 0.31eV

Carrier capture rate

Variations of BELIV transients by pulsed IR of varied spectrum in neutron irradiated detectors



E_4 hν≅ 0.51eV

E_3 hν≅ 0.41eV

E_2 hν≅ 0.36 eV

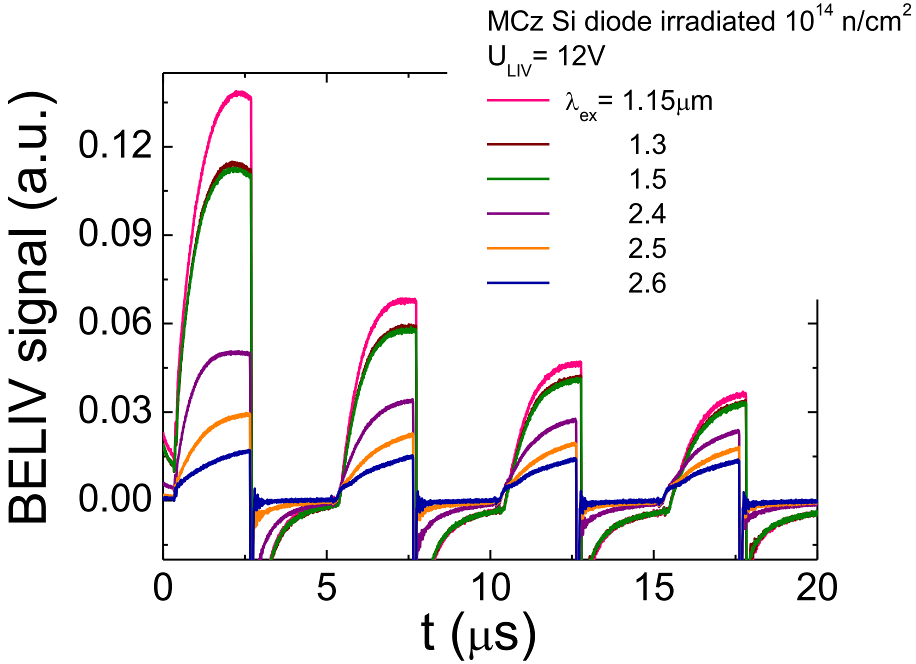
The shallowest
E_1 hν≅ 0.3 eV

MCz Si diode
10^{13} n/cm^2

Variations of BELIV transients by pulsed IR of varied spectrum in neutron irradiated detectors

The most shallow filled
$E_{\text{red threshold}} = h\nu \cong 0.5$ eV

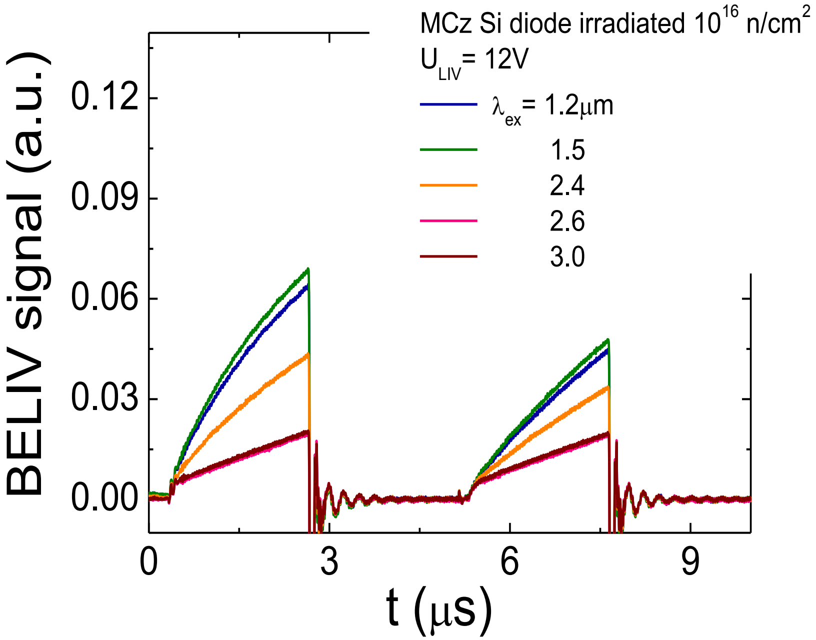
$E_{\text{deepest}} - h\nu \cong 1.08$eV



The most shallow filled,
or a half of two step generation

$E_{\text{red threhold}} = h\nu \cong 0.52$ eV

$E_{\text{deepest}} - h\nu \cong 1.08$eV



For 1E14 n/cm2 and hν> 0.83 eV possible partial recovering of a barrier, while for hν≤ 0.5 eV space charge generation current prevails (rapid capture/emission processes

For 1E16 n/cm2 only space charge generation current increases (extremely rapid capture/emission processes) while barrier capacitance is close to C_{geom}

- **A clear structure of deep levels is absent in heavily irradiated diodes >10^{14} n/cm^2 while carriers are generated by inter-band excitation.**

Items to clarify:

Whether diode/detector of the present design is functional after heavy irradiations?- doubtful

What is the system of defects and levels, which governs extraction of carriers (U_R) and state of material?- material becomes similar to insulator

Additonal issues: - if there are filled levels those compensate material;

- no, high density of various species levels is more probable those are only weakly filled by small n_0

- how rapidly these levels are able to response to external voltage changes

- fast capture of excess carrier and fast space charge generation current response

But system relaxes to equilibrium state very slowly – as estimated from I-V point-by-point measurements at T<150 K

Which models are acceptable for prediction of characteristics?

The disordered material models-?

Summary

- **Examined MW-PCT characteristics imply prevailing of intricate system of defects and reduction of majority carriers. The recombination capture lifetimes become shorter than dielectric relaxation time.**

- **Carrier emission lifetime (increase of leakage current – at U_R in I-V), follows capture lifetime (increase of serial resistance $R \sim n_0$ - at U_F in I-V)**

- **Barrier capacitance decreases to geometrical value of the diodes with enhancement of fluence. Carrier capture and emission lifetimes are short. The pointed system of deep levels can be revealed only in diodes irradiated with fluence of $<10^{14}$ n/cm^2.**

- **A clear structure of deep levels is absent in heavily irradiated diodes $>10^{14}$ n/cm^2 while carriers can be generated by inter-band excitation.**

Thanks to G.Kramberger for neutron irradiations.
E.Tuominen, J.Harkonen and J.Raisanen are appreciated
for samples (substrates and pin diodes) as well as for proton irradiations.

Thank You for attention!

Depletion aproximation for material containing only dopants:

$$\frac{d^2\psi}{dx^2} = -\frac{1}{\varepsilon\varepsilon_0}\rho(x)$$

$$\psi(x)-\psi(-\infty) = -\frac{1}{\varepsilon\varepsilon_0}\left[y\int_{-\infty}^{y}\rho(z)dz - \int_{-\infty}^{y} z\rho(z)dz\right]_{y=x}$$

$$\int_{-x_p}^{x_n}\rho(z)dz = \int_{-x_m}^{x_d}\rho(z)dz = 0$$

$$-\psi(-\infty) = V = \frac{1}{\varepsilon\varepsilon_0}\int_{-x_p}^{x_n} x\rho(x)dx$$

$$\rho(x) = e\{N_d - n(x)\}$$

$$\frac{d^2\psi(x)}{dx^2} = -\frac{e}{\varepsilon\varepsilon_0}\left\{N_d - n_0\exp\left(\frac{e\psi(x)}{kT}\right)\right\}$$

$$E^2(x) = \frac{2e}{\varepsilon\varepsilon_0}\left\{N_d\left[-\psi(x)-\frac{kT}{e}\right] + \frac{kT}{e}N_d\exp\left(\frac{e\psi(x)}{kT}\right)\right\}$$

$$\int_{x_d}^{x} dx = -\int_{0}^{\psi(x)} E^{-1}(\psi)d\psi$$

only numerical integration

assumption $[-\psi(x)] >> kT/e$

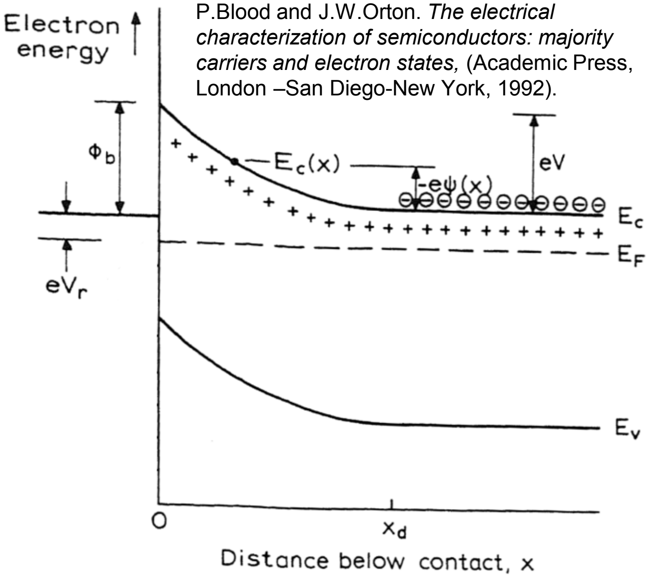
$$E^2(x) = \frac{2eN_d}{\varepsilon\varepsilon_0}\{-\psi(x)\}$$

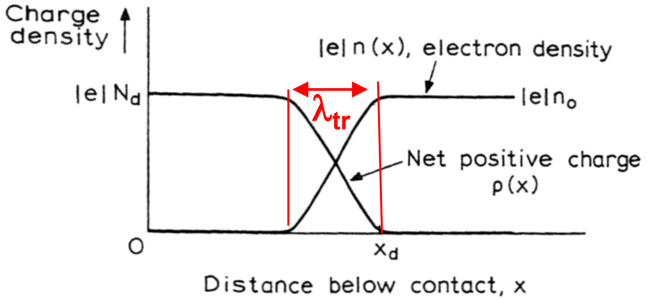
gives **depletion approximation**

$$-\psi(x) = \frac{eN_d}{2\varepsilon\varepsilon_0}(x_d - x)^2$$

$$V = \frac{eN_d}{2\varepsilon\varepsilon_0}x_d^2 \qquad E(x) = -\frac{d\psi}{dx} = -\frac{eN_d}{\varepsilon\varepsilon_0}(x_d - x)$$

P.Blood and J.W.Orton. *The electrical characterization of semiconductors: majority carriers and electron states,* (Academic Press, London –San Diego-New York, 1992).





Limitations:

for steady-state

$$n(x) = N_d\exp\left\{\frac{-e^2N_d}{2\varepsilon\varepsilon_0 kT}(x_d - x)^2\right\} = $$

$$= N_d\exp\left\{-\frac{1}{2}\left(\frac{x_d - x}{L_D}\right)^2\right\}$$

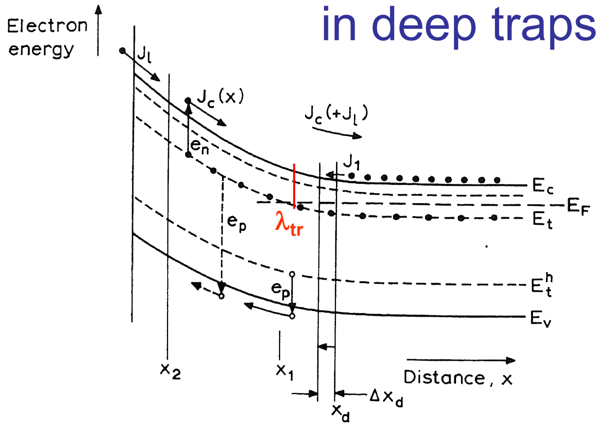
$$\rho(x) = eN_d\left\{1-\exp\left[-\frac{1}{2}\left(\frac{x_d - x}{L_D}\right)^2\right]\right\}$$

$$L_D = \left\{\frac{\varepsilon\varepsilon_0 kT}{e^2N_d}\right\}^{\frac{1}{2}} \qquad V = \frac{1}{2}\left(\frac{x_d}{L_D}\right)^2\cdot\frac{kT}{e}$$

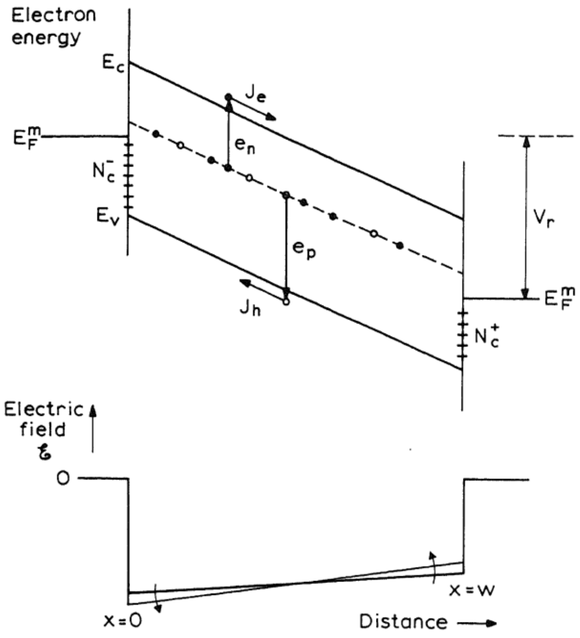
for transients

$$\tau_M = \frac{\tau_{tr}}{2} = \frac{\lambda_{tr}^2}{2\mu U_\lambda}$$

Transient currents in depletion region in deep traps containing material



Test harmonic signal $U_{ac}<kT/e$, to evaluate $C_{b,\omega}$, by control of phase shift avoiding $\Delta x_d>\lambda_{tr}$, i.e. desirable regime $E_C(x)-E_C(x_d)<kT$.



$$J_c(x) = \int_{x_2}^{x} (-e)\frac{dn}{dt}\,dx = (-e)(x-x_2)\frac{dn}{dt}$$

$$J_c(x) = (-e)x\frac{dn}{dt} + e(W-x)\left(-\frac{dp}{dt}\right)$$

$$-E(x,t) = \frac{e}{\varepsilon\varepsilon_0}(W-x)\left\{N^+ + N_t - n_t(t)\right\} + \frac{e}{\varepsilon\varepsilon_0}N_c^+(t)$$

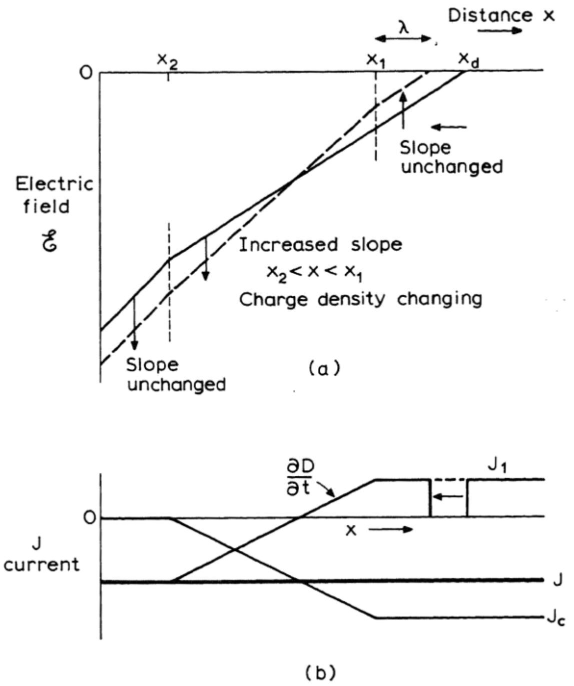
$$\left.\frac{\partial D}{\partial t}\right|_x = -e(W-x)\left(-\frac{dn_t}{dt}\right) - e\frac{dN_c^+}{dt}$$

$$V = \frac{e}{\varepsilon\varepsilon_0}\left\{(N^+ + N_t - n_t(t))\frac{W^2}{2} + N_c^+(t)W\right\}$$

$$\frac{dN_c^+}{dt} = \frac{W}{2}\frac{dn_t}{dt}$$

$$\frac{\partial D}{\partial t} = -e\left(x - \frac{W}{2}\right)\frac{dn_t}{dt}$$

$$J(t) = -e\left\{x\frac{dn}{dt} + (W-x)\frac{dp}{dt} + \left(x-\frac{W}{2}\right)\left(\frac{dp}{dt}-\frac{dn}{dt}\right)\right\} = -\frac{eW}{2}\left\{\frac{dn}{dt}+\frac{dp}{dt}\right\}$$



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