Evaluation of fluence dependent variations of capacitance and generation current parameters by transient technique

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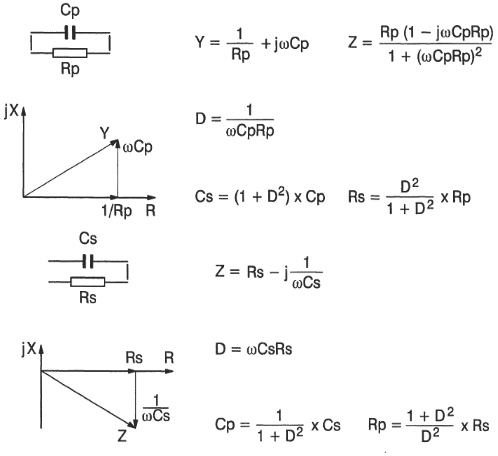
Outline

- Motivation for alternative techniques vs. impedance based frequency domain one
- Principles of **B**arrier **E**valuation by **L**inearily **I**ncreasing **V**oltage (BELIV) technique
- Fluence dependent BELIV characteristics
- Temperature dependent BELIV characteristics for reverse-biased diodes
- Detector- barrier evaluation summary
- Photo-conductivity gain in heavily irradiated full-depleted detectors
- Summary

Motivation for alternative techniques vs. impedance based frequency domain one

Limitations for impedance, frequency domain based C-V (LRC) techniques

♣ **Principle (LCR meter) "works" only if complexity (jX_C) appears due to conductance/impedance**



$$Y = \frac{1}{Rp} + j\omega Cp \qquad Z = \frac{Rp\,(1 - j\omega CpRp)}{1 + (\omega CpRp)^2}$$

$$D = \frac{1}{\omega CpRp}$$

$$Cs = (1 + D^2) \times Cp \qquad Rs = \frac{D^2}{1 + D^2} \times Rp$$

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$$D = \omega CsRs$$

$$Cp = \frac{1}{1 + D^2} \times Cs \qquad Rp = \frac{1 + D^2}{D^2} \times Rs$$

LRC phasor

Applicable only when diode can be emulated by the linear elements

$U_{ac} << kT/e$

$C_P \approx C_S\,(U_R) \approx C_{b0}\,(1+U/U_{bi})^{-1/2}$

$C_{b0}=(eN_D\varepsilon\varepsilon_0 S^2/2eU_{bi})^{1/2}$

slope C^{-2} vs $U \Rightarrow N_D$; intersect. $U_{bi}-U_F=0 \Rightarrow U_{bi}$

$U_{bi}=(kT/e)\ln(N_{Ap+}N_D/n_i^2)$

at least $U_{ac}/U_{Rdc}<<1$`

Whether standard paradigm of C-V technique is valid when diode current $i_C \approx i_{gen}$, i_{capt} for U_R -?

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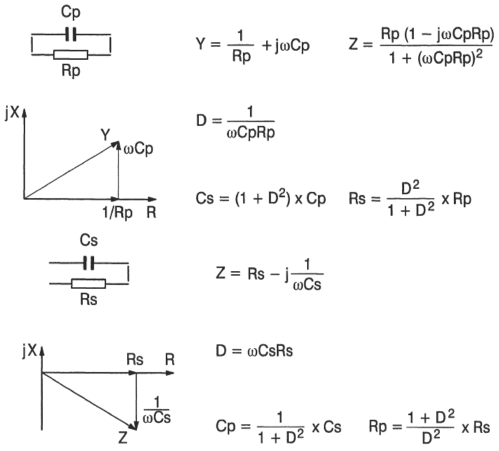

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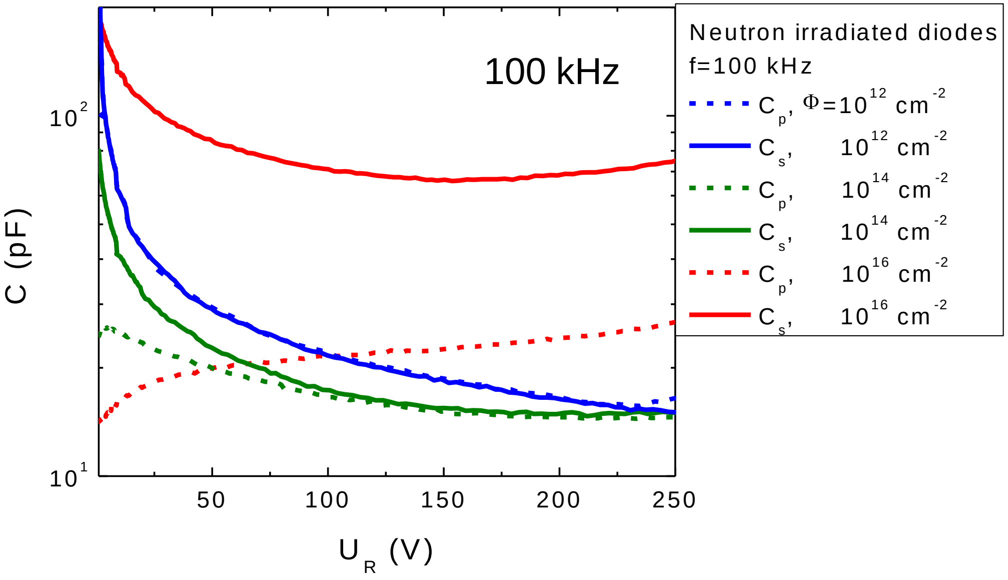
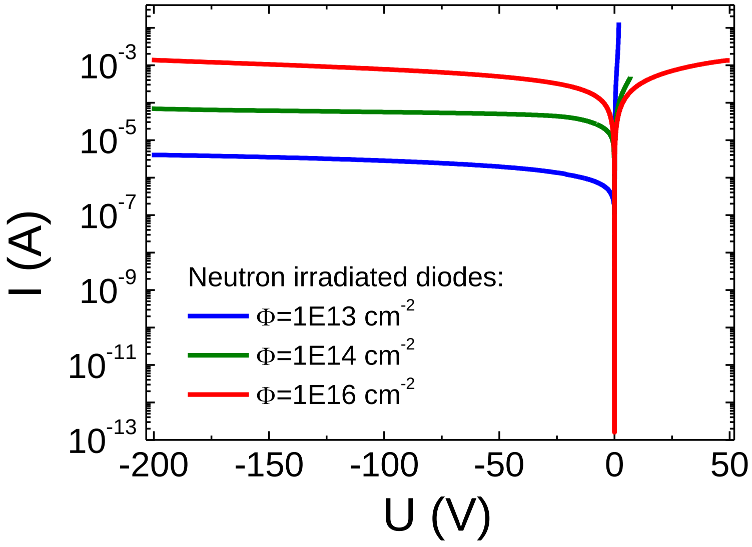
Whether standard paradigm of C-V technique is valid when diode current $i_C \approx i_{gen}$, i_{capt} & how to correlate with I-V *-?*

Why huge difference in C_P and Cs appears for heavily irradiated diode -?

Why C-V measurements are improved at high frequencies-?

Why extracted depletion voltage depends on frequency -?





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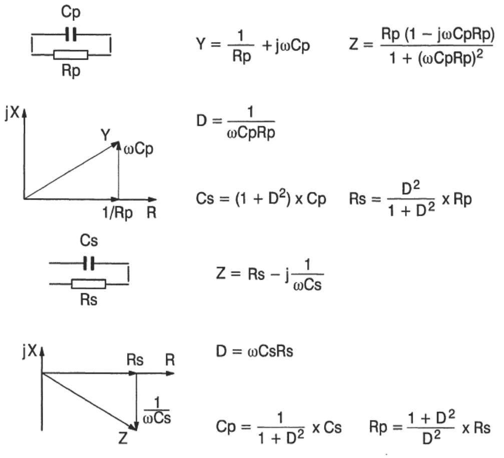

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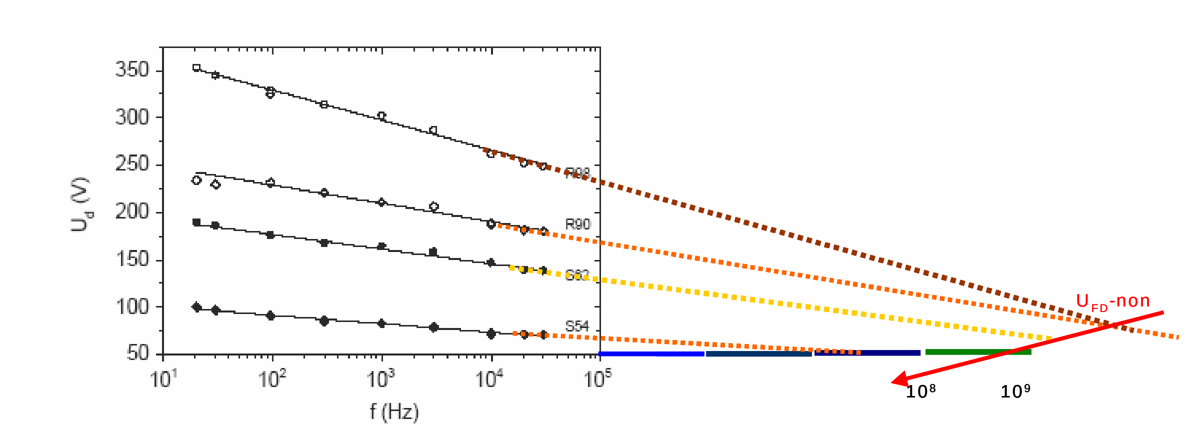

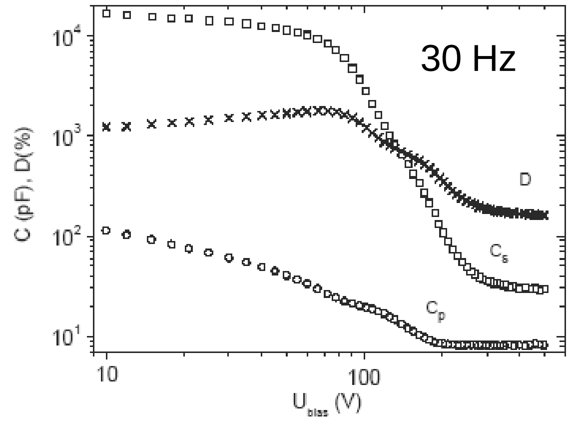

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Motivation for alternative techniques vs. impedance based frequency domain one

Limitations for impedance, frequency domain based C-V (LRC) techniques

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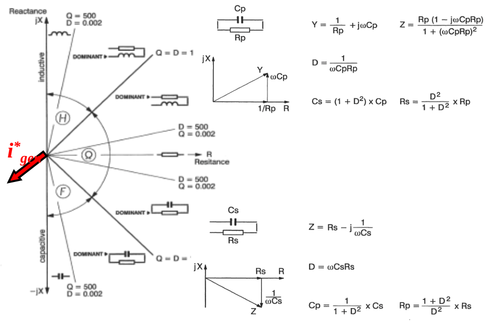


LRC phasor becomes multi-dimensional

How are the generation and carrier capture currents included into standard C-V for (heavily) irradiated pin diodes-? with large $i_{gen}=en_iw(U)S/\tau_{gen}$

$\tau_{gen}=2\cosh(E_L-E_i)/v_T\sigma N_L$ - short

$i_\Sigma=i_C+(i_{gen}+i_{diff}$ - complex quatn.)

$I_{gen,capt}=en_iw(U)S/\tau_{gen,capt}$ **becomes a complex quantity for ac $U_\sim$**

Is it possible to separate an impact of $i_{gen, capt}$ from C-V to correlate with I-V -?

Indications that LRC impedance principle and a paradigm of parameter extraction does not work anymore:

- appears huge difference between C_P and C_S - artefact of principle due to i^*_{gen},

- impossible to separate i_C and i^*_{gen},

- appears crucial reverse voltage drop:

- **e.g. $U_{gen}=i_{gen}R_{depl}=w^2(U)/\mu\tau_{gen}$ and indefinite voltage drop (<u>on junction</u> and <u>within bulk</u>) $U_{techn}=U_{gen}$**
- **U_{FD} shifts crucially to the high voltage/high frequency range due to increase of U_{gen} with U_{ext}**

- depletion width becomes indefinite *(un-known τ_{gen})*

- estimation by iteration procedure-- simulations by TCAD/SPICE or approach of positive root $w(U_{ex})=[2\varepsilon\varepsilon_0(U_{bi}+U_{ext})/\{eN_D(1+2\varepsilon\varepsilon_0/eN_D\mu\tau_{gen})\}]^{1/2}$ *– valid for U_{ac}/U_{dc}<<1; necessary additional parameters)*

- intricate ($w(U_{ext})$) dependence on frequency, temperature, voltage - due to τ_{gen}

- appears an artificial effective doping $N_{ef}^{art}= N_D(1\pm 2\varepsilon\varepsilon_0/eN_D\mu\tau_{gen})$ – *seeming variations*

♣Technical limitations for LRC-meters based measurements

- necessary to make measurements in the range of low U_R voltages to avoid the impact of i_{gen},~ $U^{1/2}$ - *LRC meters with small ac voltage $U_\sim$<<kT/e*

- dc and ac voltage sources connected in series (dependence on $R_{in\ dc}$),

- noise (U_{ns}) suppressed dc voltage sources due to small U_{ns} <<$U_\sim$,

- no additional loops (capacitors, resistors), limitations to ground for LRC-meters with wide range of external dc voltages

Motivation for alternative techniques vs. impedance based frequency domain one

♣ Principles to include $i_{gen,\ capt}$

- To include dominant physical processes, analysis of $C_{bj}(U)=\varepsilon\varepsilon_0 S/w(U)$ is an alternative way with ***estimation of w(U) by iteration procedure- approach of positive w(U) root using*** $U_{gen}=w^2/\mu\tau_{gen,capt}$

$$w(U_{R,ext}) = \sqrt{\frac{2\varepsilon\varepsilon_0 (U_{bi} + U_{R,ext} \pm U_{gen,capt})}{eN_D}} \cong \sqrt{\frac{2\varepsilon\varepsilon_0 (U_{bi} + U_{R,ext})}{eN_D\left(1 \pm \frac{2\varepsilon\varepsilon_0}{eN_D \mu\tau_{gen+,capt-}}\right)}}$$

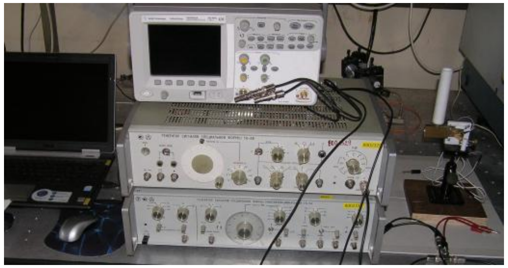
valid for $U_{ac}/U_{dc}{<<}1$ and leads to different $N_{eff}=N_D$ $\boldsymbol{(1\pm 2\varepsilon\varepsilon_0/eN_D\mu\tau_{+gen,-capt})}$ for $\omega\approx 1/\tau_{gen}$ (+) and for $\omega\approx 1/\tau_{capt}$ (-)

- ***Evaluation of w(U_{junct}) by simulations by TCAD/SPICE etc.***

$$i_\Sigma(U) = i_C[w(U)] + \frac{en_i w(U)S}{\tau_{gen,capt}}$$

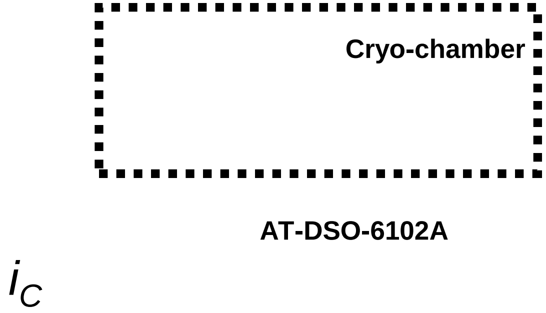
♣ Alternative measurement techniques capable to separate components

BELIV technique



$U(t)=U_P/\tau_{PL}t=At$

LIV ramp $A=U_P/\tau_{PL}=\partial U/\partial t$



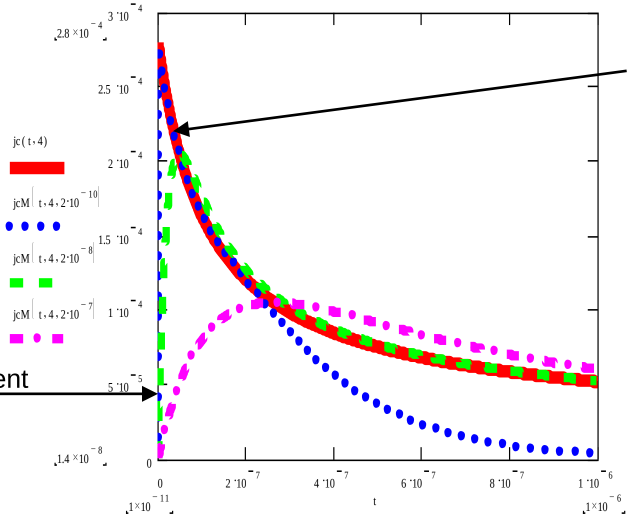
LIV always starts from U(t)=0

τ_{PL}= 10 ns ⇒ 500 µs
U_P= 0.01 ⇒ 5 V

C_b= 2 pF ⇒ 40 µF with resolution ~ 0.2 pF | (2-20 pF)

$U_C=i_C*50\ \Omega$ =10 mV ⇒ 4 pF$|_{A=5*E8\ V/s}$

BELIV technique, model and simulations



Charge extraction current

Displacement current

Reverse bias

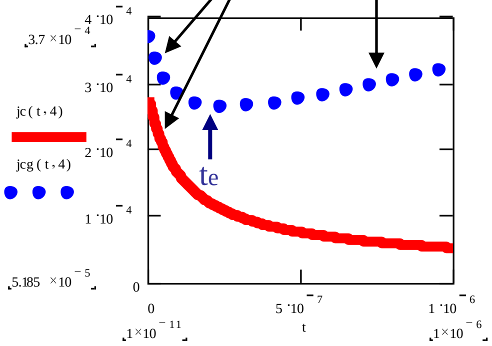
$$i_C(t) = \frac{dq}{dt} = \frac{\partial U}{\partial t}\left(C_b + U\frac{\partial C_b}{\partial U}\right) = AC_{b0}\frac{1+\frac{At}{2U_{bi}}}{\left(1+\frac{At}{U_{bi}}\right)^{3/2}}$$

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

Short transient processes acting in series due to t_{D}, τ_{DR}, τ_{capt}, τ_{gen} *etc* (to complete a circuit) determine a delay,- reduction of the initial displacement current step. Similar effect perturbs the C-V characteristic at $U_R \to 0$ measured by impedance technique (LRC-meters).

Charge extraction

Charge generation



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

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

BELIV technique U_F model

$U(t)=U_P/\tau_{PL}t=At$

Forward bias

$U_F(t)=At-R_L i_{\Sigma F}(t),$

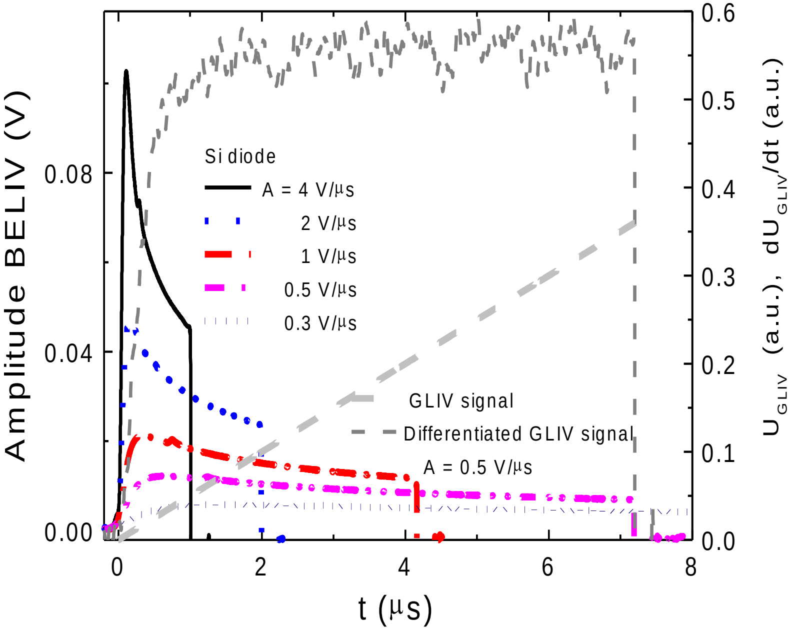
$$i_{\Sigma F}(t)=i_{CF}(t)+i_{Cdiff}(t)+i_R(t)+i_{diffF}(t)=$$

$$\frac{\partial U_F(t)}{\partial t}\{C_{b0}\frac{(1-\frac{U_F(t)}{2U_{bi}})}{(1-\frac{U_F(t)}{U_{bi}})^{3/2}}+C_{diff\ 0}[1+\frac{eU_F(t)}{k_BT}]e^{\frac{eU_F(t)}{k_BT}}\}+\frac{en_iw_0}{2\tau_R}(1+\frac{U_F(t)}{U_{bi}})^{1/2}+\mathrm{i}_{diff\,\infty}(e^{eU_F(t)/k_BT}-1)$$

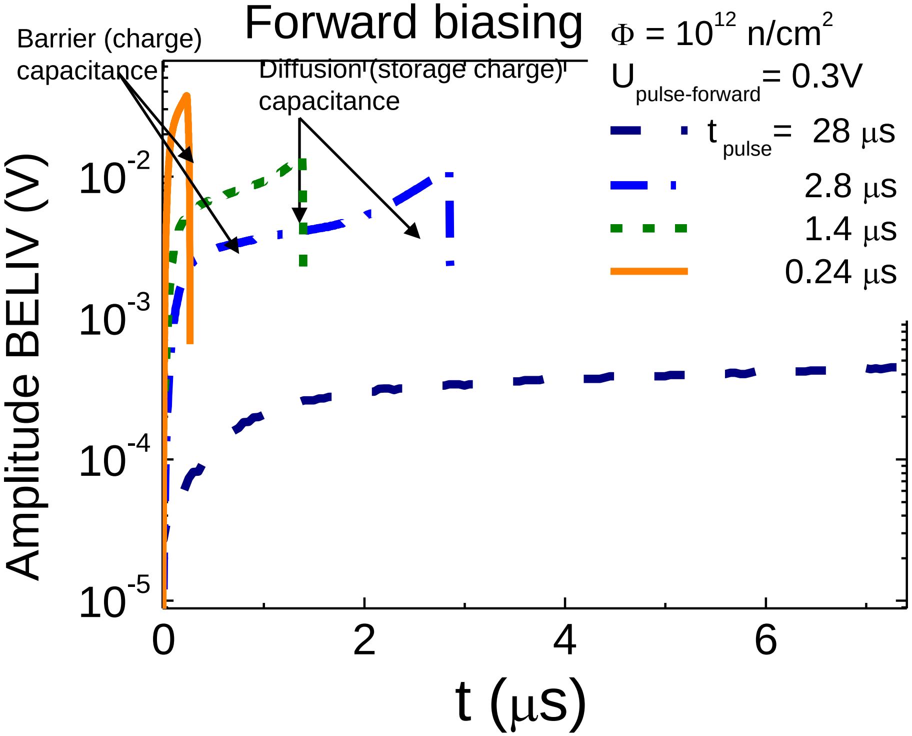
Transcendental, iterative simulations

BELIV transients – measurement technique

Reverse biasing



Forward biasing



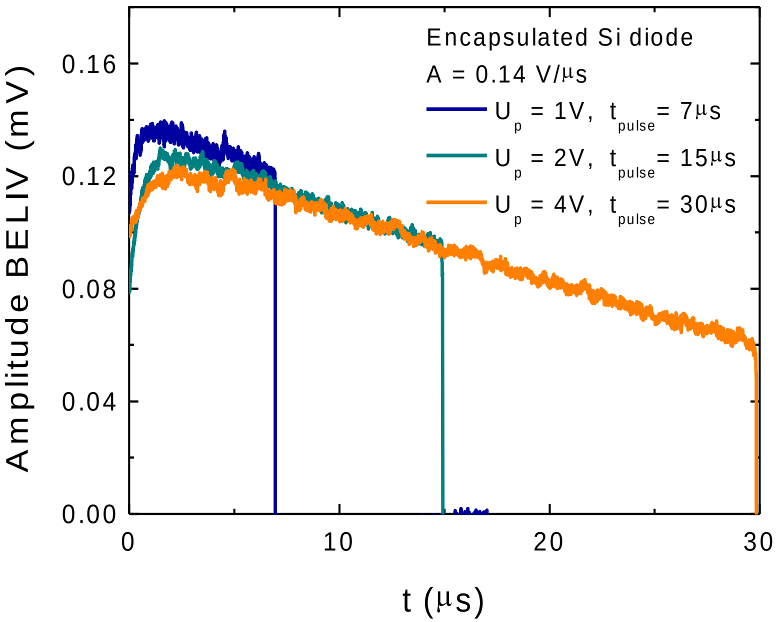
a

b

a- **B**arrier **e**valuation by **l**inearly **i**ncreasing **v**oltage (BELIV) technique based on charge extraction current transients measured in the non-irradiated and irradiated with small fluence pin diode at reverse (U_R) biasing by LIV pulses.

b- Charge injection BELIV transients for forward (U_F) biased pin diode irradiated with small fluence varying ramp *A* of LIV pulses.

BELIV transients – measurement technique



U_R pulse duration dependent BELIV transients at a constant LIV ramp is equivalent to C_b -V~t

BELIV transients on WODEAN pad-detectors neutron-irradiated with fluences 10^{12} -10^{16} n/cm^2

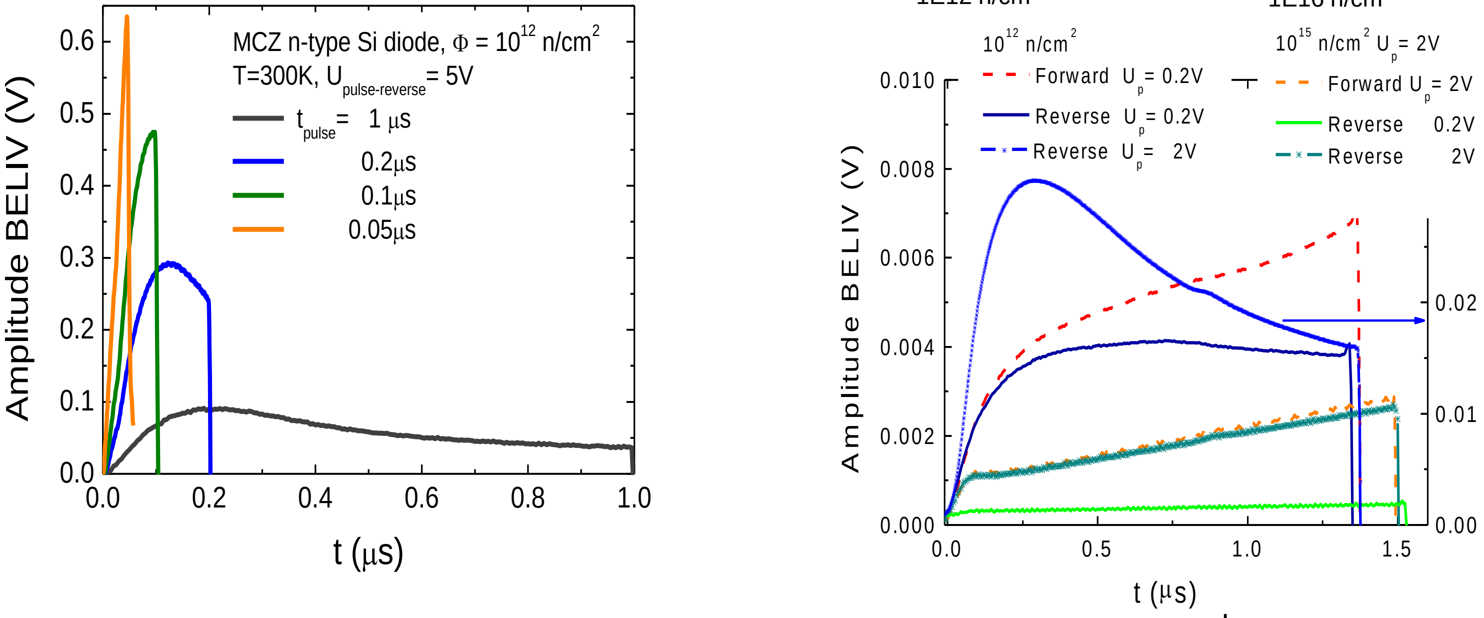
Reverse bias

Barrier capacitance prevails for short LIV pulses

Reverse & Forward bias

C_b
dominates for
1E12 n/cm^2

Igen & irec
dominate for
1E16 n/cm^2



a b

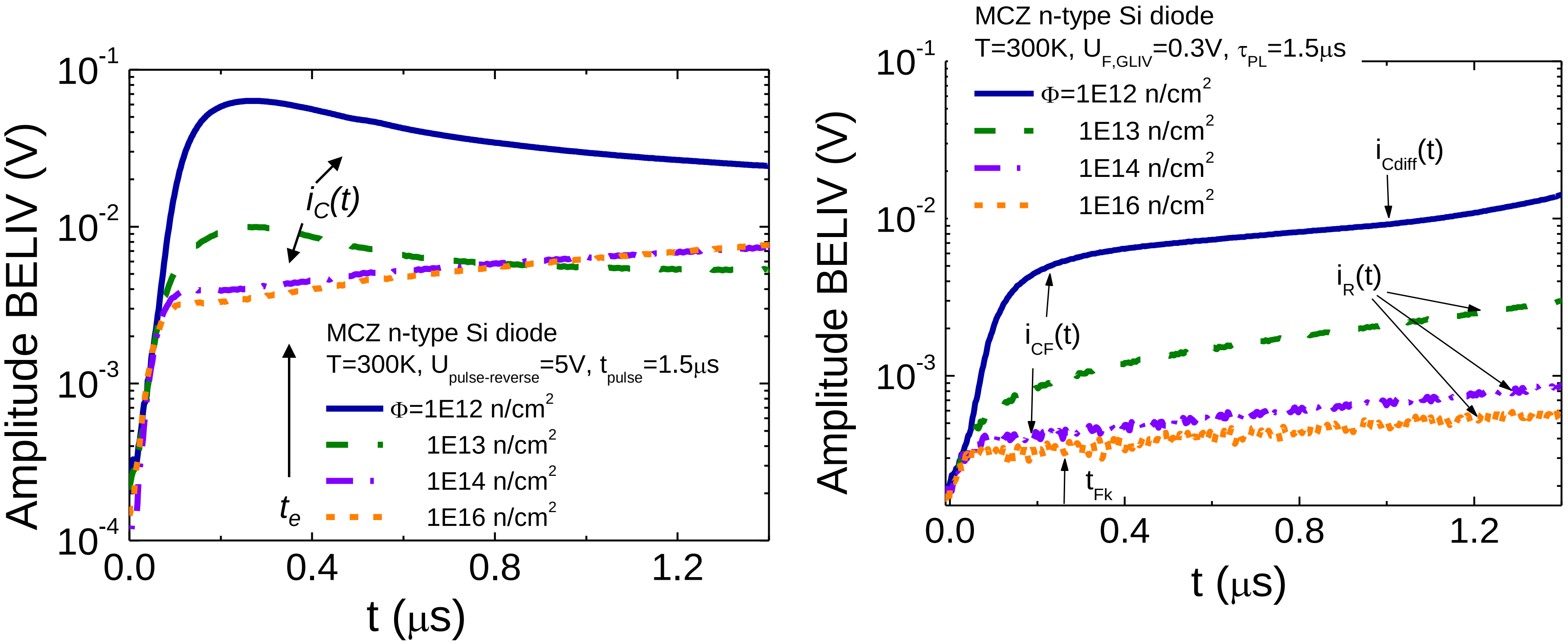
a- LIV pulse duration (LIV ramp) dependent BELIV transients at reverse (U_R) bias. b- Comparison of charge extraction (U_R) and injection (U_F) BELIV transients measured on diodes irradiated by neutrons of different fluence.

To separate the displacement, generation/capture and diffusion currents, a wide range of duration/voltage and perfect LIV pulses are necessary.

For diodes irradiated with rather small fluence charge extraction current prevails for Rev biasing, while charge storage (diffusion) capacitance dominates for Frw biased diodes.

In heavily irradiated material generation and recombination currents dominate. Voltage on junction is governed by $U_{jnc}=At-i\Sigma RL$

BELIV results –dependence on fluence

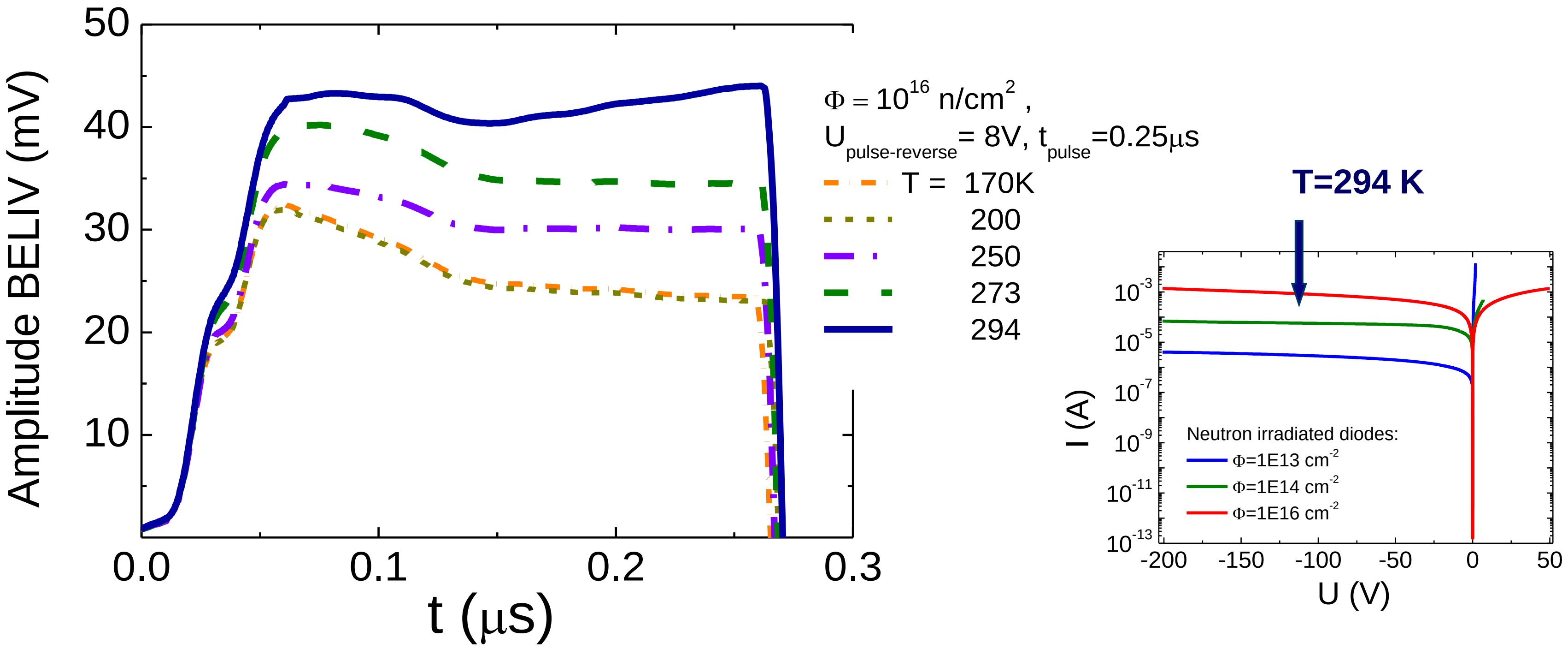


a

b

a- Variations of BELIV transients with irradiation fluence for reverse biased Si pin pad-detector at the same LIV parameters (A= 3 MV/s, τ_{PL} =1.5 μs). b- Injection current BELIV transients for different fluence neutron irradiated Si pin diodes. The extreme points (t_e, t_{Fk}) are denoted on transients.

BELIV results –dependence on temperature

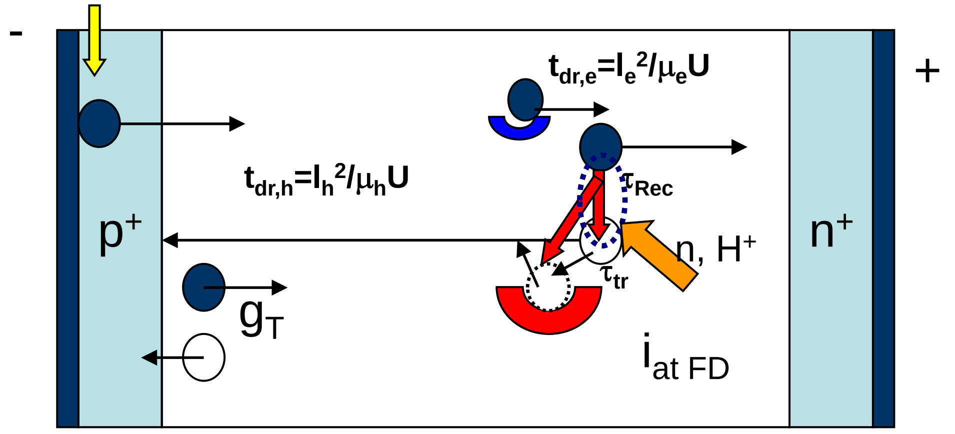


Temperature dependent variations of BELIV transients in heavily (with fluence of 10^{16} n/cm^2) irradiated Si pin diode.

U_{bi} still exists (for 1E16 n/cm^2) but diode at RT resembles a photo-resistor at large U_{bias}

Photo-conductivity gain (PCG)

for $t_{dr,e}<t_{dr,h}$ to keep el. neutrality additional carrier(s) is injected from electrode or thermally generated in vicinity of electrode



$PCG=t_{dr,h}/t_{dr,e}$ ⇒ CCE>1 if $t_{dr,e}<t_{dr,h}<\tau_{Rec}$

CCE⇒0 for $\tau_{Rec}<t_{dr}$

- radiation induced generation (trapping) centers *(increased density with fluence)* enhance probability for PCG processes;

- reduction of t_{dr} by enhancement of $U>U_{FD}$ and by reduction of $d\sim l_h$;

- resolvable PCG pulses if time gap t_{ar} between arrival of HE particles $t_{ar}>\tau_{tr}$

Summary: detector- barrier evaluation by LIV

For barrier evaluation better to control $U_{bi}=(kT/e)ln(N_A N_D/n_i^2)$

BELIV shows N_D is invariable, barrier exists, detector functional, but necessary to shift the operational range towards high (ω) frequency/short time domain range, to decrease bias voltage (to suppress i_{gen}) etc.

Optimization of the detector' functionality is possible only by a trade-off among desirable parameters:

- necessity to shift the time domain τ_{TD} towards short shaping time $\tau_{TD} \approx 1/\omega$ is compatible with LHC operation regime, but, to reduce an impact of $i_{gen,\ rec}$, it is desirable to keep $\tau_{rec,gen} > \tau_{TD} > \tau_{DR}$ (reduction of τ_{DR} is possible by enhancement of doping);
- to suppress $i_{gen,\ rec}$ - reduction of the operational voltages, temperature and base thickness d;
- to reach full-depletion – enhancement of operational voltage, but increases a problem with $i_{gen} \sim U^{1/2}$;
- to reduce impact of g-r noises – enhancement of detector volume $V=Sd$ through base thickness or area S ($\Rightarrow$ 3-D detectors);
- to approach a photo-conductivity gain regime (to increase CCE) enhancement of operational voltage and proper reduction of base thickness d;

Summary

- **Validity of a simple paradigm (standard C-V method) of the parameter extraction from C-V characteristics in irradiated diodes should be verified for every experimental regime and adjusted by selecting ω, U_R, U_{ac}, T parameters**

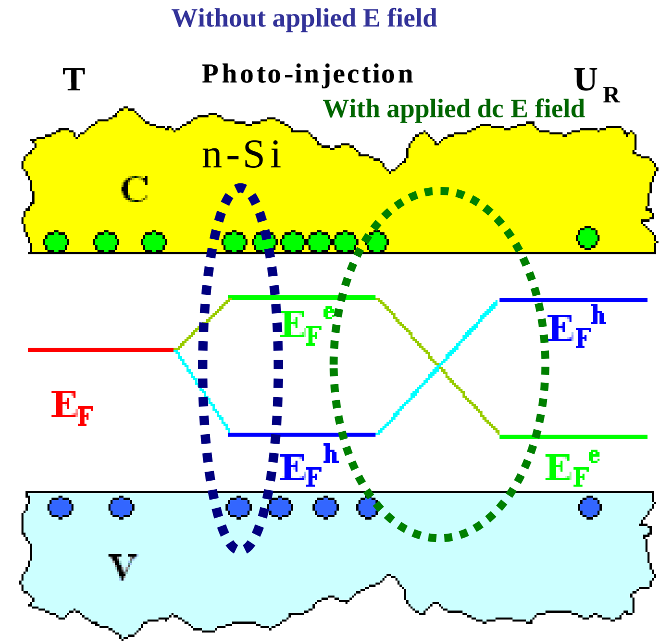
- **Developed BELIV transient technique enables one to control variations of U_{bi} and generation current dependent on fluence and temperature. Increase of generation current for reverse biased diode and reduction of diffusion capacitance/current due to recombination of injected carriers in forward biased diodes leads to the symmetric (*Rev/Frw*) I-V/C-V transient characteristics. Symmetry of these characteristics indicate the dominant mid-gap centers/clusters with pinned E_F.**

- **BELIV shows U_{bi} and N_D is invariable and detector is functional, while in heavily irradiated detectors for 20 Hz< ω <10 MHz deterioration of characteristics is determined by $\tau_{capt,gen}$.**

- **Optimization of the detector' functionality is possible only by a trade-off among desirable parameters. CCE can be increased through proper design of detector (d) and applied detection regimes (U, $\tau_{response}$) to reach PCG.**

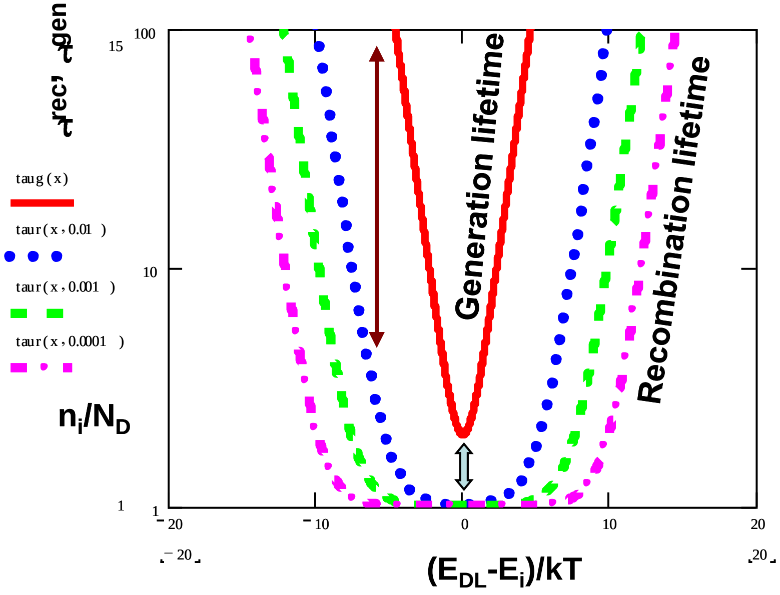
Thank You for attention!

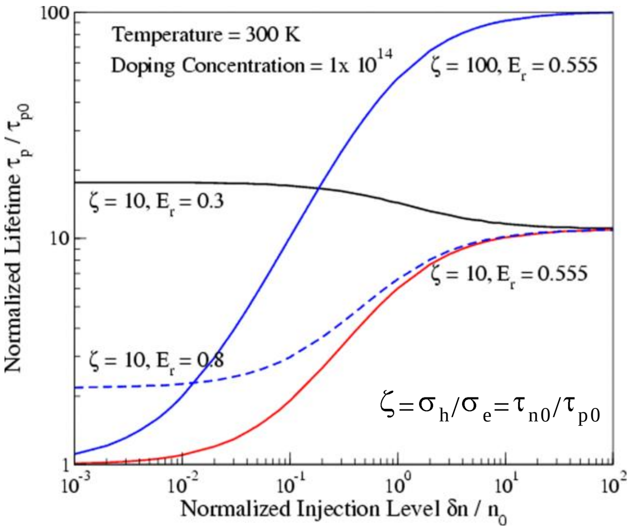
Trivial remarks concerning SRH relations between recombination – generation lifetime



$n^e \cdot p^e - n_i^2 = 0$ R>0 $n^e \cdot p^e < n_i^2$

Eqv. $n^e p^e > n_i^2$ G<0

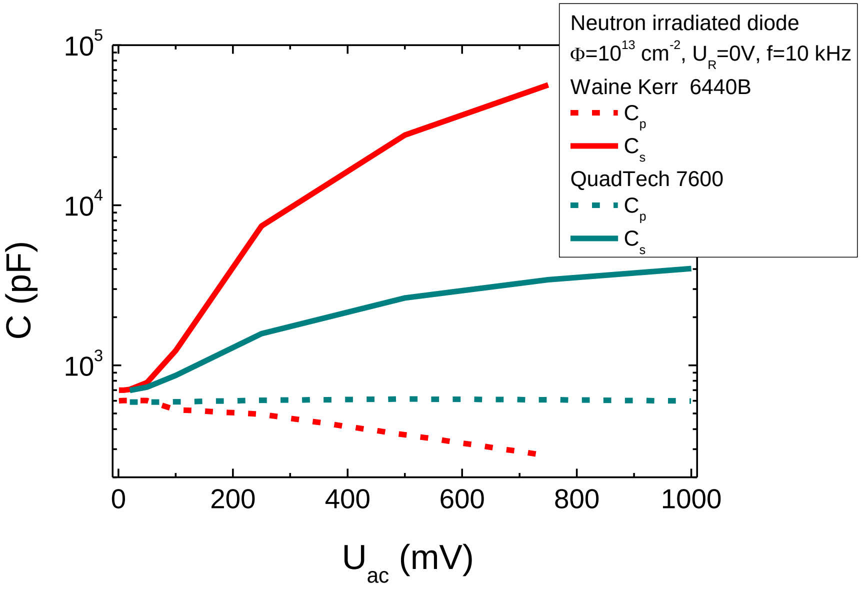


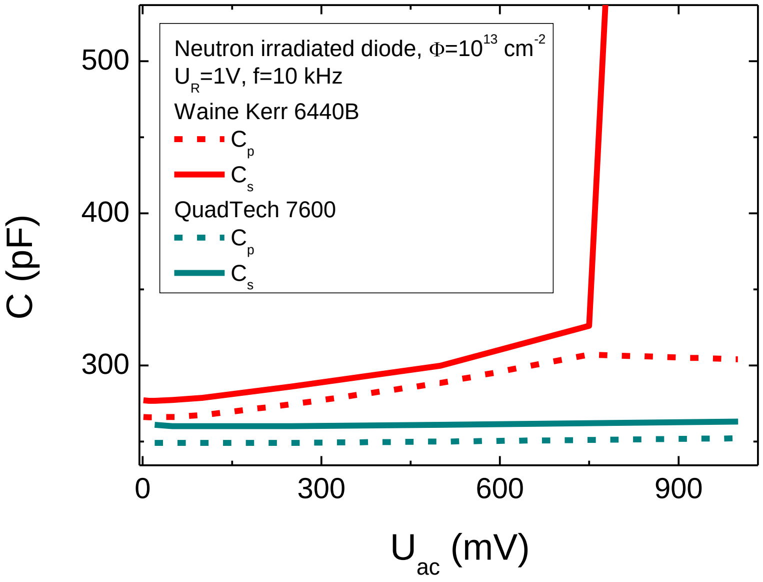


$$\tau_{rec} = \frac{\Delta n}{R} = \frac{1}{v\sigma N_{DL}}\left[1 + \frac{2n_i}{n^e}\cosh\left(\frac{E_{DL}-E_i}{kT}\right)\right]\Big|_{n^e >> n_i} = \frac{1}{v\sigma N_{DL}}$$

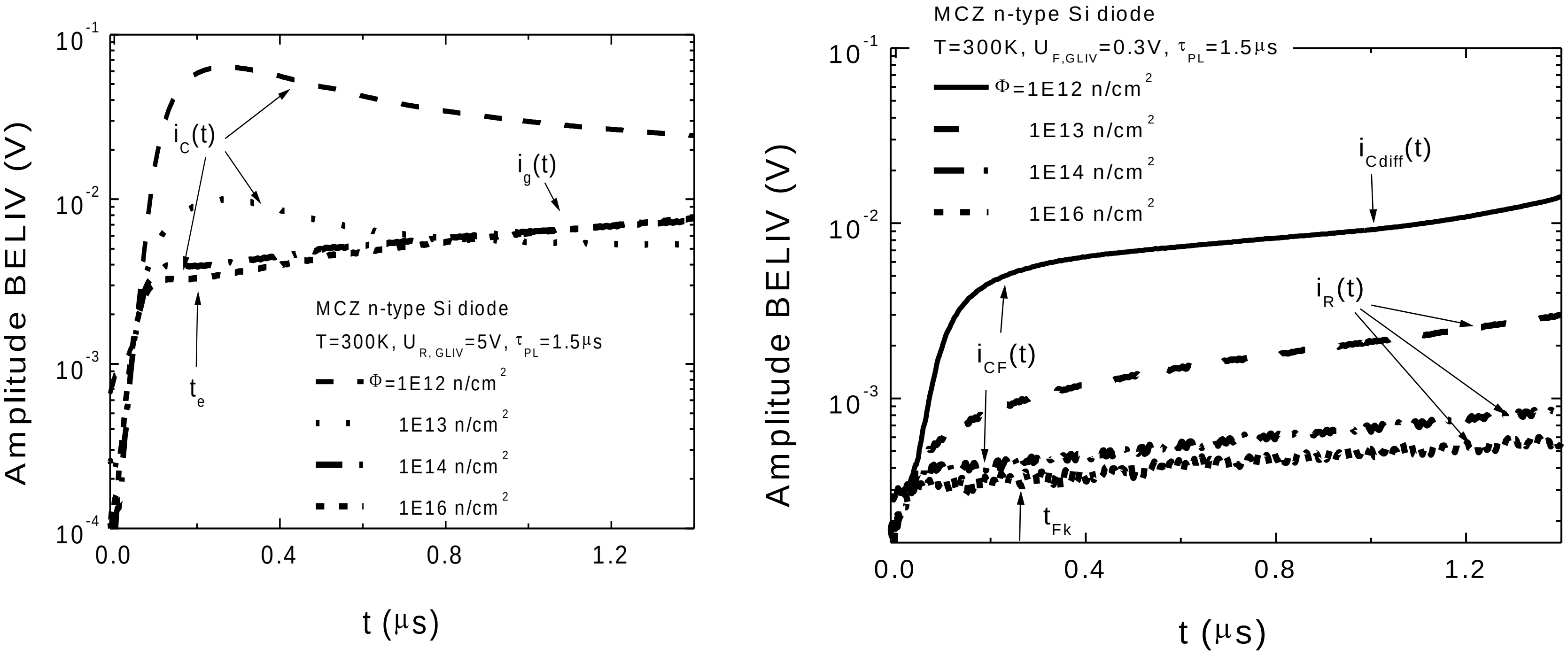
$$\tau_{gen} = n_i / G = \frac{2\cosh\left(\frac{E_{DL}-E_i}{kT}\right)}{v\sigma N_{DL}}$$

Calibration of LRC-meters





BELIV results –dependence on fluence



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Relation among $C_{b,,}$ R_{depl} and LRC: Y,R_p ,C_p

$$p_n(x) = p_{n0}[\exp\frac{eU}{kT} - 1]e^{-\frac{x}{L_p}} \qquad U = U_0 + U_a e^{i\omega t}$$

$$p_n(x)|_{U_0} = p_{n0}[\exp\frac{eU_0}{kT} - 1]e^{-\frac{x}{L_p}}$$

$$p_n(x)|_{U_0+U_a e^{i\omega t}} = p_{n0}[\exp\frac{e(U_0+U_a e^{i\omega t})}{kT} - 1]e^{-\frac{x}{L_p}}$$

$$\Delta p_{n_a}(x)|_{U_a} = p_{n0}[\exp\frac{e(U_0+U_a e^{i\omega t})}{kT} - 1]e^{-\frac{x}{L_p}} - p_{n0}[\exp\frac{eU_0}{kT} - 1]e^{-\frac{x}{L_p}} =$$

$$= p_{n0}e^{-\frac{x}{L_p}}[\exp\frac{e(U_0+U_a e^{i\omega t})}{kT} - 1 - \exp\frac{eU_0}{kT} + 1] = p_{n0}\exp\frac{eU_0}{kT}e^{-\frac{x}{L_p}}[\exp\frac{eU_a e^{i\omega t}}{kT} - 1] =$$

$only\ \ if\ \ U_a << \frac{kT}{e}$

$$\approx p_{n0}\exp\frac{eU_0}{kT}e^{-\frac{x}{L_p}}\frac{eU_a e^{i\omega t}}{kT} = p_{n0}\exp\frac{eU_0}{kT}\frac{eU_a}{kT}e^{-\frac{x}{L_p}}e^{i\omega t} = p_{n0}\exp\frac{eU_0}{kT}\frac{eU_a}{kT}e^{-\frac{x}{\lambda_p}}$$

$when\ \ if\ \ \frac{L_p}{x}t = \tau_{capt,R}$

$$\lambda = \frac{L_p}{\sqrt{1+i\omega\tau_{capt,R}}}$$

$$j_p|_{U_0} = -eD_p\frac{\partial p_n|_{U_0}}{\partial x} = eD_p[\exp(\frac{eU_0}{kT}) - 1]$$

$$j_p|_{U_{ac}} = -eD_p\frac{\partial \Delta p_n|_{U_{ac}}}{\partial x} \cong \frac{eU_{ac}}{kT}(j_p + j_{p,dif})\sqrt{1+i\omega\tau_{capt,R}}$$

$$Y = \frac{j_p}{U_{ac}} = \frac{e}{kT}(j_p + j_{p,dif})\sqrt{1+i\omega\tau_{capt,R}} = G + i\omega B = \frac{1}{R_{depl}} + i\omega C_b$$