Modeling of carrier kinetics in pCVD* diamond detectors

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Samples

- Polycrystalline detectors from the RD42 CERN Collaboration (manufactured by DEBID, UK)

Substrate	UTS1 (1998)			CDS92 (2000)
SAMPLES	P13[a]	P15[a]	P16[a]	P4[b]
size [mm^2]	5×5	5×5	5×5	5×5
thickess [μm]	664 ± 2	663 ± 2	656 ± 2	470 ± 2
active area [mm^2]	7	7	7	7
irradiation [10^{14} n/cm^2]		1.5 ± 0.2	20 ± 3	
CCD[c] [μm]	140	110[d]	85[e]	245

[a] Chromium and gold contacts Ohio, Rutgers

[b] Al ohmic contacts made at Ohio State University

[c] Measured in the pumped state.

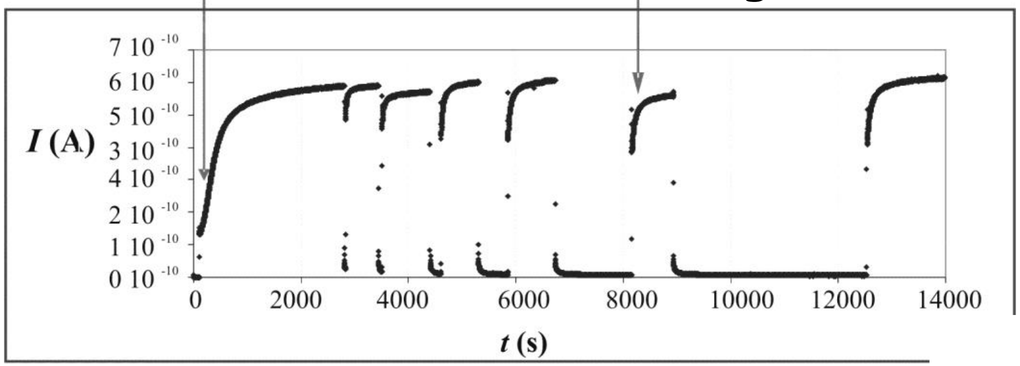
[d] Equal to the value measured before irradiation

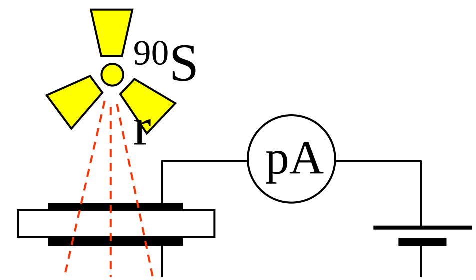
[e] Equal to 120 μm before irradiation.

Experimentals *two types of measurement:*

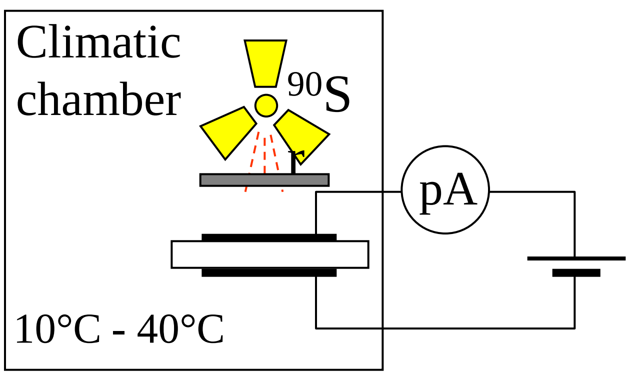
β Pumping from the:

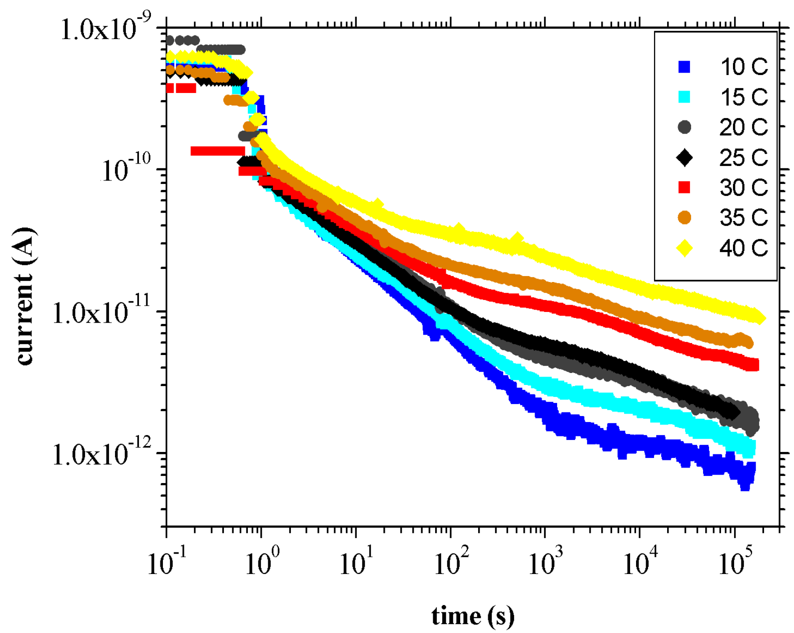
- totally depumped state;
- After thermal fading (from the partially depumped state)





Persistent current after removal of the source (at different *T*)





Aim of the model:

- To evaluate the defect level parameters: capture cross section, concentration, position in the bandgap
- To relate the defect parameters to the device performances

Outline of the presentation:

- Assumptions
- Calculations
- Fit of the experimental data
- Conclusions so far

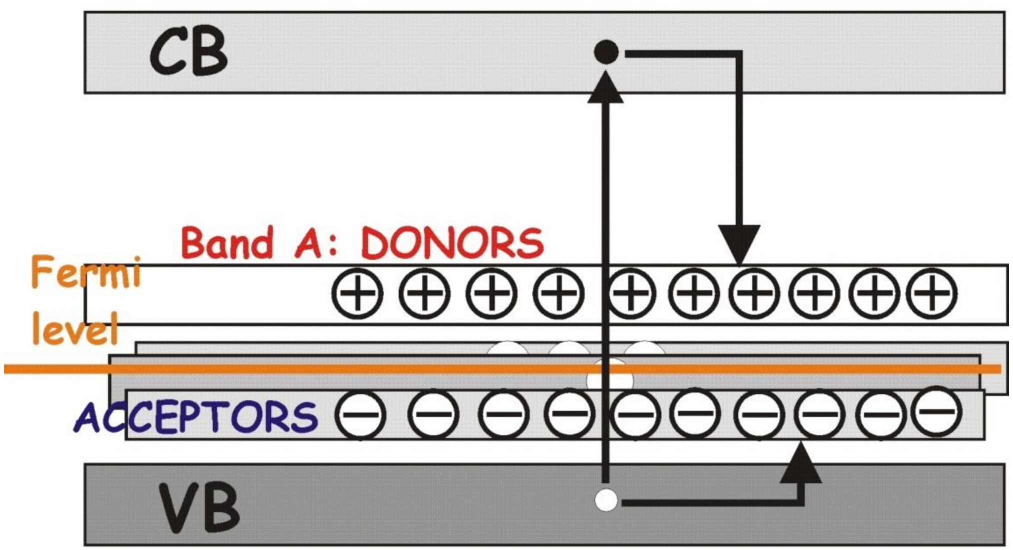
Assumption 1: defect bands

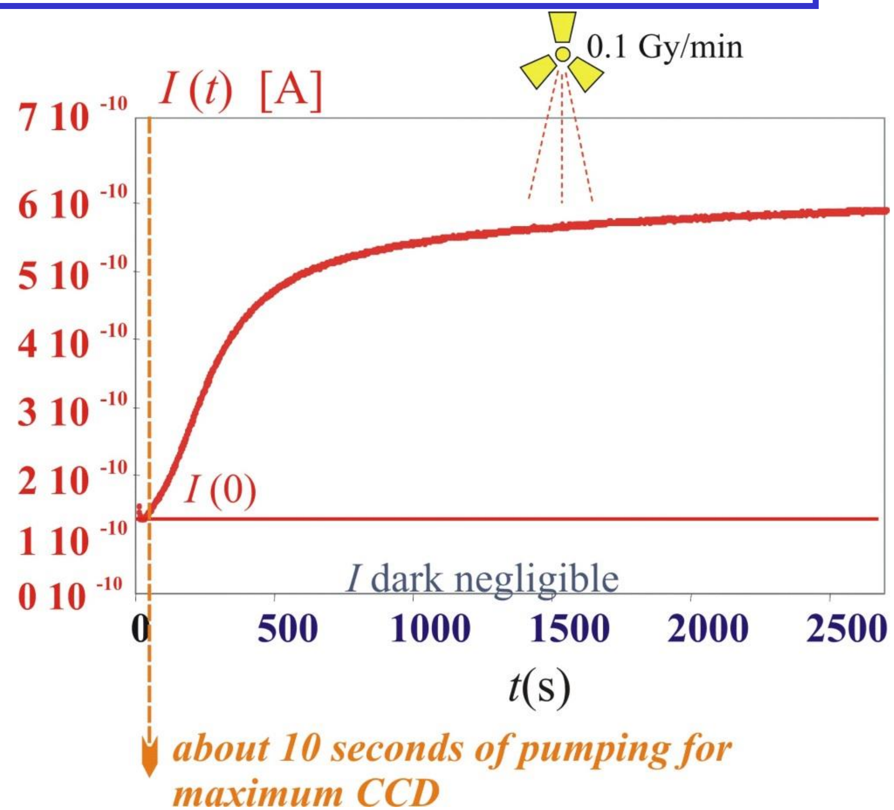
We assume the existence of:

- **a DONOR centre** (σ_r, N_r)
- **and an ACCEPTOR centre** (m components: $\sigma_1, N_1, \ldots, \sigma_i, n_i, \ldots \sigma_m, N_m$), both with their spread in energy.

The parameters are determined by fitting the experimental data.

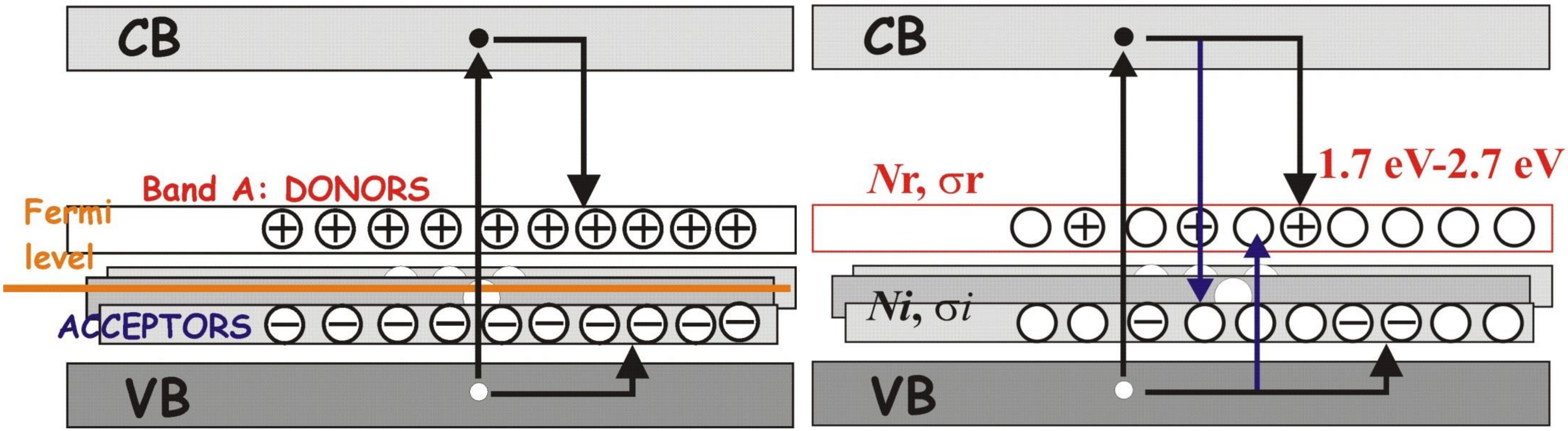
The ACCEPTOR CENTRE is BELOW THE DONOR CENTRE in the bandgap, otherwise we should see a different behaviour of the *pumping* current.





Assumption 2: *We neglect interband transitions and (only in the pumping stage) emission processes*

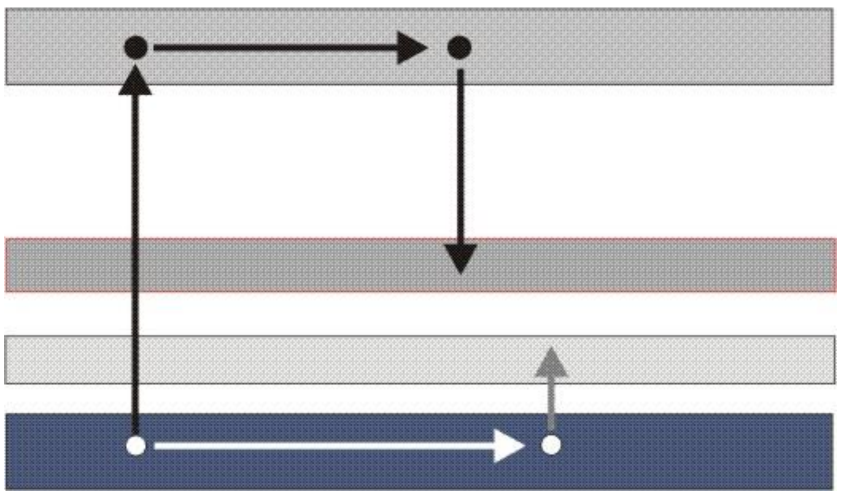
pumping *Dynamic equilibrium*



•Energy limits of the donor centre (1.7-2.7 eV from VB) determined by photoconductivity measurements [M. Bruzzi, S. Lagomarsino, S. Sciortino, et al. *Phys. Stat. Sol. (a)* **199**, #1, 138-144 (2003)]

•Identification of the recombination centre with the luminescence band A by electroluminescnce measurements [Manfredotti et al., *Appl. Phys Lett*. **67** 3376 (1995)]

3. Quasi-equilibrium (QE) approximation



$$\frac{dn}{dt} \approx 0$$

$$\frac{dp}{dt} \approx 0$$

•The population of the VB and CB *does not change* significantly with respect to the population of the defect bands

$$n \approx 0, \qquad p \approx 0$$

The values of the populations are also negligible

The QE approximation is very well satisfied (a posteriori verification)

4. Single-carrier approximation

From the experimental results of RD42 and the “linear-model”*

* H.Kagan for The RD42 Collaboration NIMA **514** (2003) 79-86

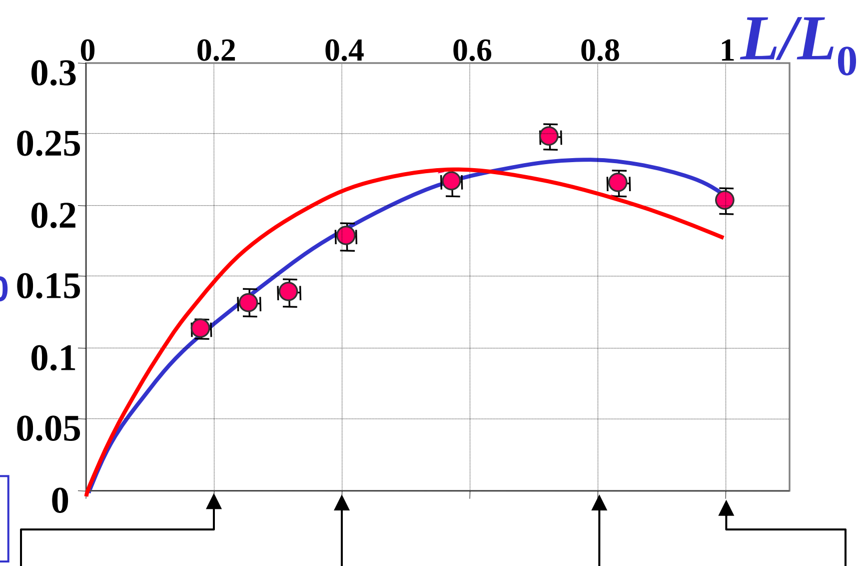
It is well known that material removal from the substrate side of a polycrystalline CVD diamond film produces at first an enhancement, due to the poorest quality of the near-substrate material,

Assuming a double-carrier conduction yields a very poor fit:

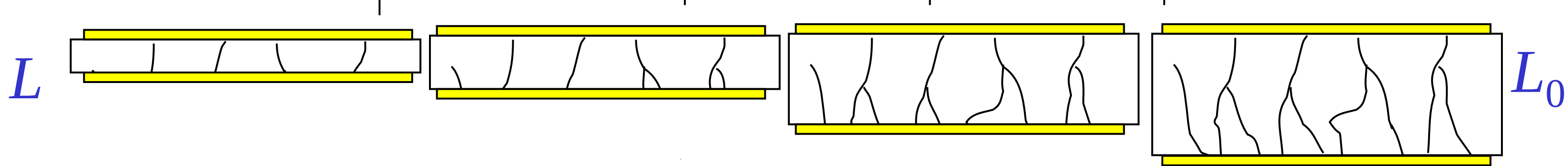
50% *n*, 50% *p*: χ^2=11

The single-carrier assumption yields the best fit:

5% *n*, 95% *p*: χ^2=1.4



The shape of this dependence is related to the relative weight of electron and holes conduction



Rate equations

- N_r and σ_r (σ_r^n) are the concentration and the capture cross sections for holes (electrons) of the recombination centre.
- $\{N_1, \ldots, N_m\}$, $\{\sigma_1, \ldots, \sigma_m\}$ ($\{\sigma_1^n, \ldots, \sigma_m^n\}$) are the concentrations and the capture cross sections for holes (for electrons) of the trap centre.
- $q_i(t)$ will represent the **numeric** concentration of charged empty states of type i.
- $q_r(t)$ will represent the numeric concentration of charged empty states of the recombination centre.
- The pair generating factor of the β radiation is denoted by g.
- The concentration of holes (electrons) and their thermal velocity are labelled p (n) and v_p (v_n), respectively.

The rate equations **under the hypotheses 1 and 2** are:

$$\frac{dp}{dt} = g - pv_p\left[\sum_{i=1}^{m} q_i(t)\sigma_i + (N_r - q_r(t))\,\sigma_r\right],$$

$$\frac{dq_i}{dt} = -pq_i(t)v_p\sigma_i + n\,(N_i - q_i(t))\,v_n\sigma_i^n,$$

$$\frac{dn}{dt} = g - nv_n\left[\sum_{i=1}^{m} (N_i - q_i)\,\sigma_i^n + q_r(t)\sigma_r^n\right],$$

$$\sum_{i=1}^{m} q_i(t) + n = q_r(t) + p$$

The last equation is THE NEUTRALITY CONDITION

QE approximation (hypothesis 3) and numerical solution of the rate equations

We adopt the QUASI-EQUILIBRIUM APPROXIMATION (QE), justified by the negligibility of the free carriers concentration with respect to the total concentration of defects (order of 10^4 cm^{-3} against $> 10^{12}$ cm^{-3}).

$$\boxed{\begin{aligned} \frac{dp}{dt}, \frac{dn}{dt} &\approx 0; \\ p, n &\approx 0 \end{aligned}}$$

Accordingly, the neutrality condition can be written:

$$\boxed{\sum_{i=1}^{\mathrm{m}} q_i(t) = q_r(t) + p - n \cong q_r(t)}$$

and the rate equations yield:

$$p = \frac{g}{v_p} \times \frac{1}{N_{\mathrm{r}}\sigma_{\mathrm{r}} + \sum_{i=1}^{\mathrm{m}} q_i \left(\sigma_i - \sigma_{\mathrm{r}}\right)}$$

$$n = \frac{g}{v_n} \times \frac{1}{\sum_{i=1}^{\mathrm{m}} N_i \sigma_i^n + \sum_{i=1}^{\mathrm{m}} q_i \left(\sigma_{\mathrm{r}}^n - \sigma_i^n\right)}$$

$$\boxed{I(t) = e\left(n\mu_n + p\mu_p\right) EA}$$

The fit function can be calculated numerically

Single-carrier approximation (hypothesis 4) and analytical solution of the rate equations

Under the single-carrier assumption:

$$\boxed{n \ll p}$$

which is equivalent to:

$$\boxed{\begin{gathered}\sigma_{\rm r}^n \gg \sigma_{\rm r}, \\ \sigma_i \gg \sigma_i^n \\ \sigma_{\rm r} \sim \sigma_i\end{gathered}}$$

The hole concentration p is proportional to the current I:

$$p = \frac{I}{e\mu_{\rm p} A E}$$

If we denote the total charge collected by:

$$Q = \int_0^t I(t')dt',$$

we can solve each equation:

$$\frac{dq_i}{dt} = -pq_i(t)v_{\rm p}\sigma_i,$$

in terms of Q, as follows:

$$q_i(Q) = N_i \times \exp\left(-\frac{v_{\rm p}}{e\mu_{\rm p} A}\sigma_i Q\right).$$

$$I(Q) = \frac{e\mu E A g}{v_{\rm p}} \times \left[N_{\rm r}\sigma_{\rm r} + \sum_{i=1}^{\rm m} (\sigma_i - \sigma_{\rm r})\, N_i \exp\left(-\alpha_i Q\right)\right]^{-1}$$

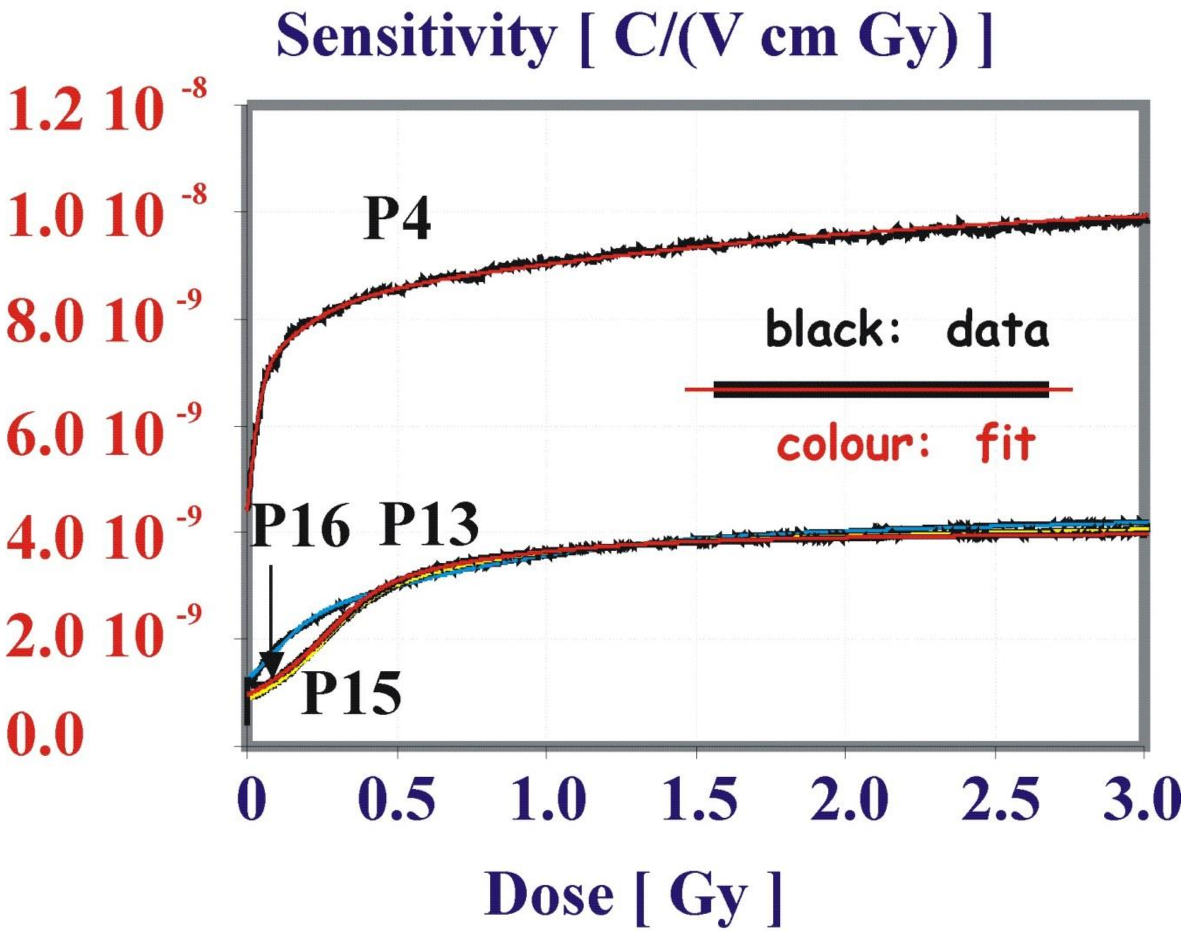
with:

$$\alpha_i = \frac{v_{\rm p}}{e\mu_{\rm p} E A}\sigma_i$$

Fit of the experimental data: pumping

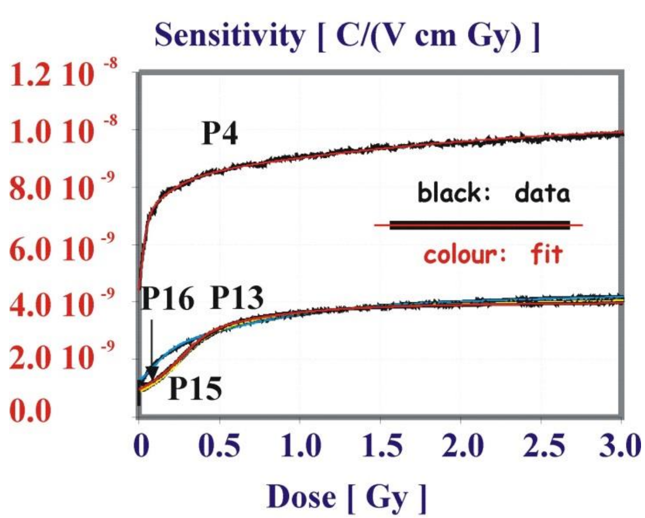
A set of m=3 trap components, and a single recombination centre, with cross sections ranging from $\approx 10^{-16}$ to $\approx 10^{-14} cm^2$, fits very well to our measurements ($\chi^2 \approx 4 \div 8$)

The stable level value is proportional to the concentration of the recombination centres



Fit of the experimental data: pumping

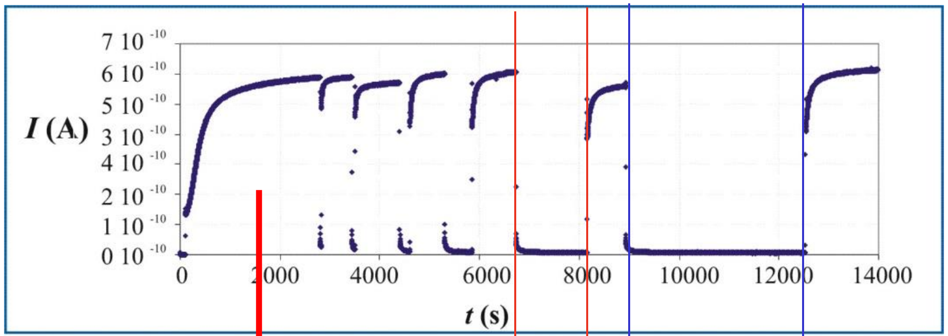
	# 1	# 1′	# 2	# 3	r	SAMPLES
σ_i $[10^{-15}\mathrm{cm}^2]$	68 ± 17	38 ± 10	7.5 ± 2.5	0.7 ± 0.1	0.50 ± 0.25	UTS1 (1998)
N_i $[10^{14}\mathrm{cm}^{-3}]$	0.65 ± 0.10		3.3 ± 0.3	50 ± 25	50 ± 25	P13
	0.12 ± 0.1	2.2 ± 0.1	2.7 ± 0.1	50 ± 25	50 ± 25	P15
		2.1 ± 0.2	2.1 ± 0.3	50 ± 25	50 ± 25	P16
σ_i $[10^{-15}\mathrm{cm}^2]$	54 ± 15		6.8 ± 2.0	0.75 ± 0.1	0.55 ± 0.25	CDS92 (2000)
N_i $[10^{14}\mathrm{cm}^{-3}]$	0.20 ± 0.05		0.39 ± 0.01	23 ± 12	23 ± 12	P4



From 1998 to 2000

- Decrease of the defect concentration
- Same type of defect centres

Thermal fading measurements



Δt

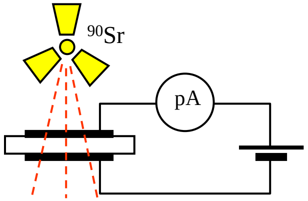
Δt is increased exponentially

Plot the number density of charged traps as a function of fading time Δt

$$I(Q) = \frac{e\mu E A g}{v_{\mathrm{p}}} \times \left[N_{\mathrm{r}}\sigma_{\mathrm{r}} + \sum_{i=1}^{\mathrm{m}} (\sigma_i - \sigma_{\mathrm{r}})\, N_i \exp(-\alpha_i Q) \right]^{-1}$$

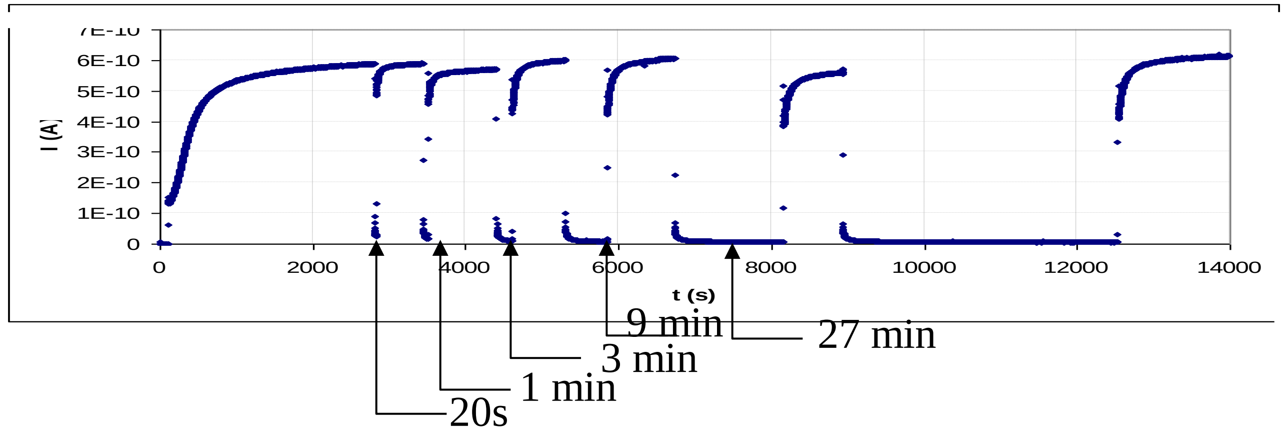
$$\alpha_i = \frac{v_{\mathrm{p}}}{e\mu_{\mathrm{p}} E A}\sigma_i$$

$$I(Q) = \frac{e\mu E A g}{v_{\mathrm{p}}} \times \left[N_{\mathrm{r}}\sigma_{\mathrm{r}} + \sum_{i=1}^{\mathrm{m}} (\sigma_i - \sigma_{\mathrm{r}})\, q_i(\Delta t) \exp(-\alpha_i Q) \right]^{-1}$$



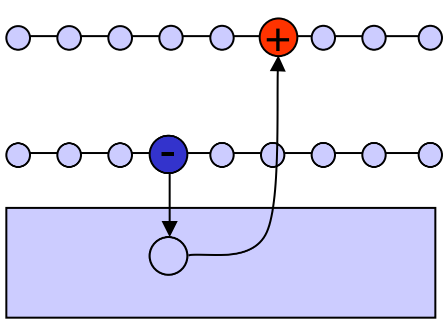
Thermal fading analysis

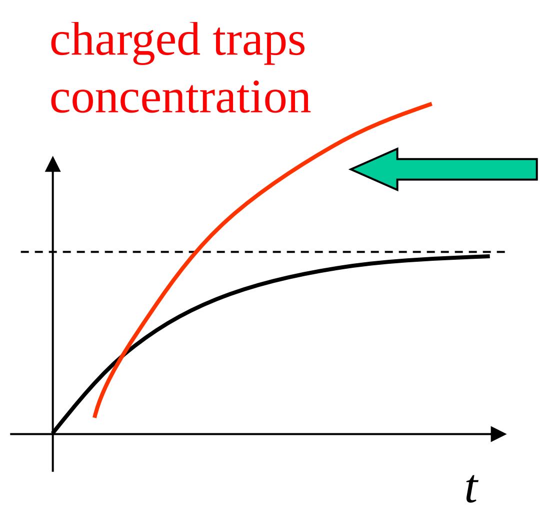
The analysis of radiation induced current after different times of thermal fading at room temperature

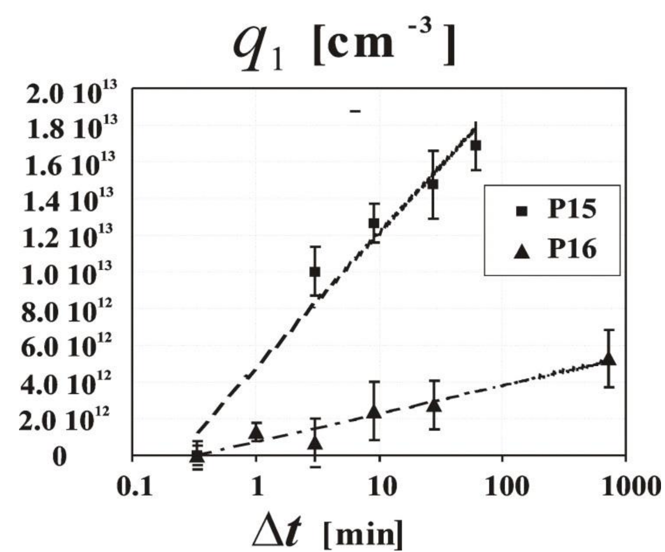


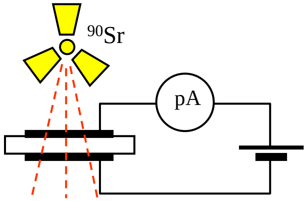
The thermal empting of a localized trap level would give an exponential dependence of the population of the level on time

As a matter of fact, the experimental dependence is more likely a logarithmic one









β Radiation Induced Current (βRIC)

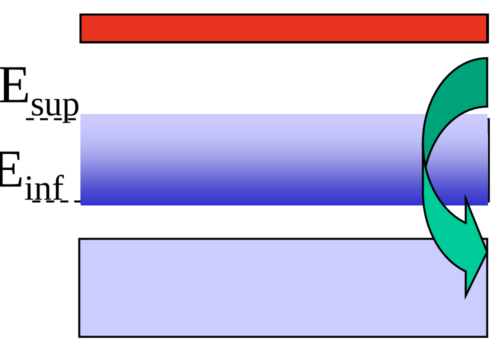
The logarithmic dependence can be explained by assuming a uniform distribution of level in the band gap with E_{sup}-E_{inf}>>kT

$$N_i - q_i(t) = \int_{E_{inf}}^{E_{sup}} \frac{dN_i}{dE} \exp\left(-s \cdot e^{-\frac{E}{KT}} t\right) dE = \frac{dN_i}{dE} \int_{E_{inf}}^{E_{sup}} \exp\left(-\frac{t}{\tau}\right) dE$$

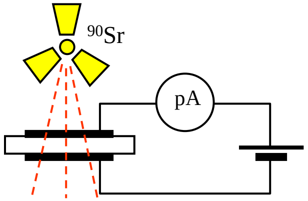
$$-\frac{dq_i(t)}{dt} = \frac{dN_i}{dE} \int_{E_{inf}}^{E_{sup}} \frac{1}{\tau} \exp\left(-\frac{t}{\tau}\right) dE = \frac{dN}{dE} kT \frac{e^{-t/\tau_{sup}} - e^{-t/\tau_{inf}}}{t} \cong \frac{dN_i}{dE} kT \frac{1}{t}$$

$$\boxed{\frac{1}{\tau} = s_i \times \exp\left(-\frac{E}{kT}\right)}$$

$$\boxed{s_i = \sigma_i N_{\mathrm{V}} v_{\mathrm{p}}}$$

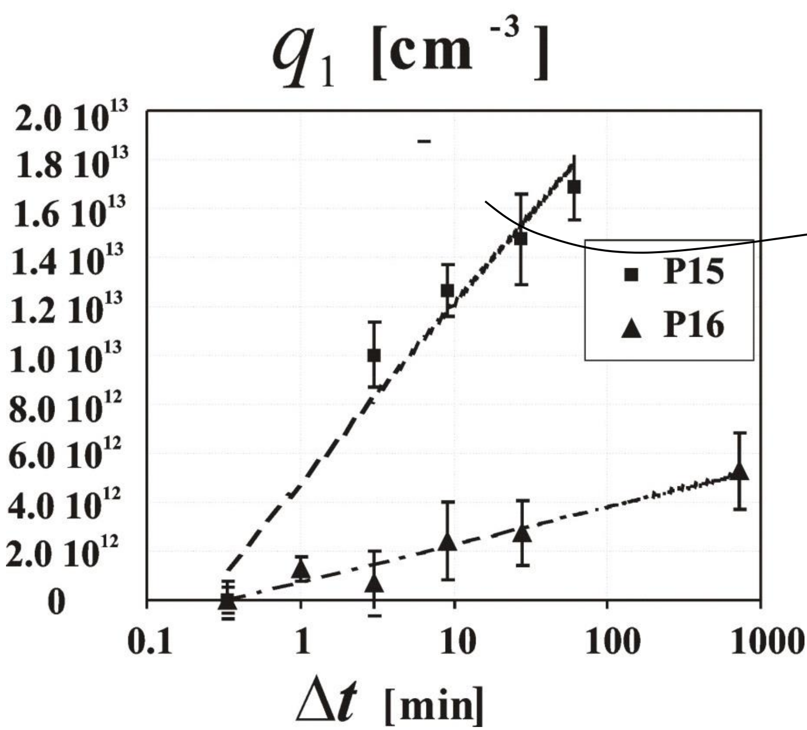


$$q_i(t) = A + \frac{dN_i}{dE} kT \cdot \ln t$$

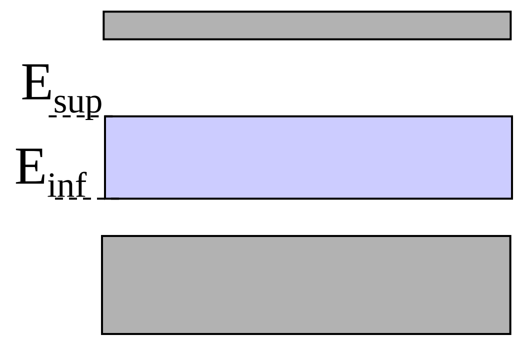


β Radiation Induced Current: thermal fading

The rate of change of the *population* of empty (charged) states vs. $\log \Delta t$ is proportional, via temperature, to the density of levels per unit energy in the band-gap, and gives a direct measurement of this quantity.

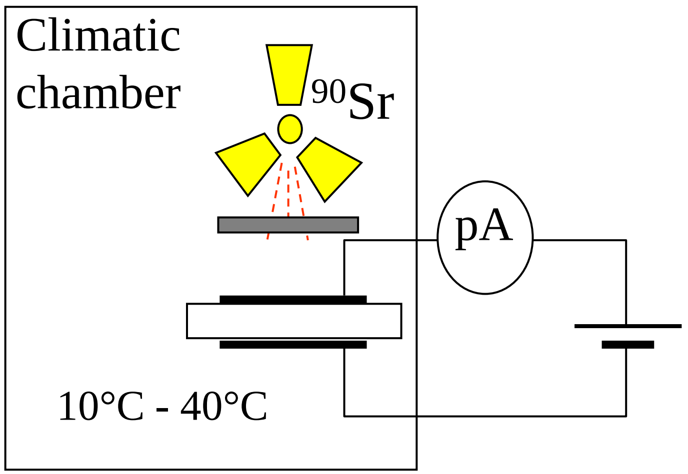


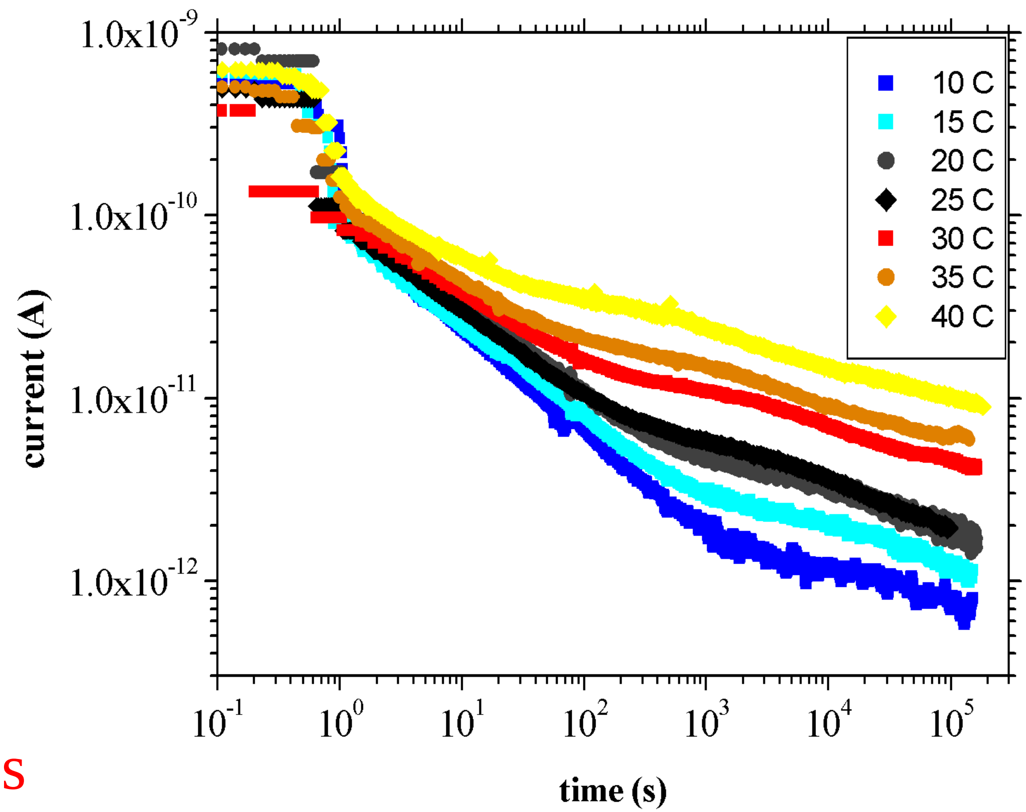
$$\frac{dN_1}{dE} kT$$



Persistent current analysis

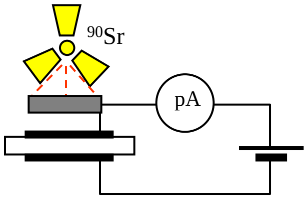
Persistent current after removal of the source (at room *T and near room T*)





Measurement over 10^5 s

In a log-log scale



Persistent Induced Current (PIC)

No retrapping (first order kinetics). Recombination is favoured with respect to retrapping for the whole duration of the measurement ($\approx 10^5$ s), at room temperature.

$$\frac{dq}{dt} = -\frac{dN}{dE}\frac{d}{dt}\int_{E_{\rm inf}}^{E_{\rm sup}} \mathcal{P}(E,t)dE = \frac{dN}{dE}kT\frac{\exp\left(-\frac{t}{\tau_{\rm sup}}\right)-\exp\left(-\frac{t}{\tau_{\rm inf}}\right)}{t}$$

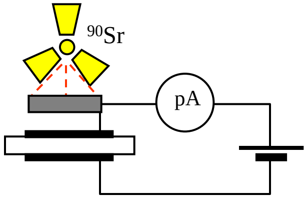
$$\tau_{\rm sup} = \frac{1}{s}\exp\left(-\frac{E_{\rm sup}}{kT}\right), \qquad \tau_{\rm inf} = \frac{1}{s}\exp\left(-\frac{E_{\rm inf}}{kT}\right)$$

Quasi-equilibrium (QE) approximation. The extremely low concentration of free carriers, compared with the density of defects, ensures that the rate of relaxation of the traps is, at any instant, equal to the rate of recombination.

$$\sum_{i=1}^{\rm m}\frac{dq_i}{dt} = p\left(N_{\rm r}-q_{\rm r}\right)\sigma_{\rm r}v_{\rm p} \qquad \sum_{i=1}^{\rm m}\frac{dq_i}{dt} \approx pN_{\rm r}\sigma_{\rm r}v_{\rm p}$$

$$g = p(\infty)N_{\rm r}\sigma_{\rm r}v_{\rm p} \longrightarrow \sum_{i=1}^{\rm m}\frac{dq_i}{dt} = \frac{p}{p(\infty)}g$$

$$\frac{J}{J_\infty} = \frac{p}{p(\infty)} \qquad \boxed{J = \frac{J_\infty}{g}kT\sum_{i=1}^{\rm m}\frac{dN_i}{dE}\frac{\exp\left(-\frac{t}{\tau^i_{\rm sup}}\right)-\exp\left(-\frac{t}{\tau^i_{\rm inf}}\right)}{t}}$$

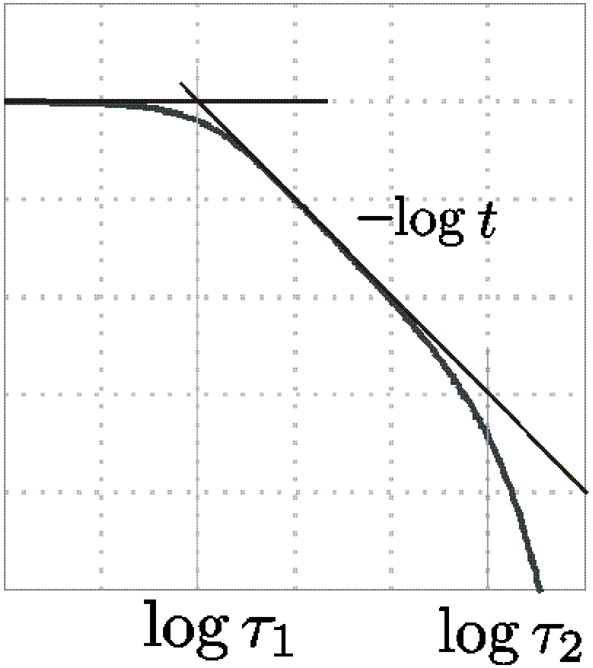


Persistent Induced Current (PIC)

Fit function

$$\log\left(\frac{\exp\left(-\frac{t}{\tau_2}\right)-\exp\left(-\frac{t}{\tau_1}\right)}{t}\right)$$

A component



In our case

$t << \tau_{sup}$ →

$$J = J_{\mathrm{dark}} + \sum_{i=1}^{\mathrm{m}} J_i \frac{1-\exp\left(-\frac{t}{\tau_i}\right)}{t/\tau_i}$$

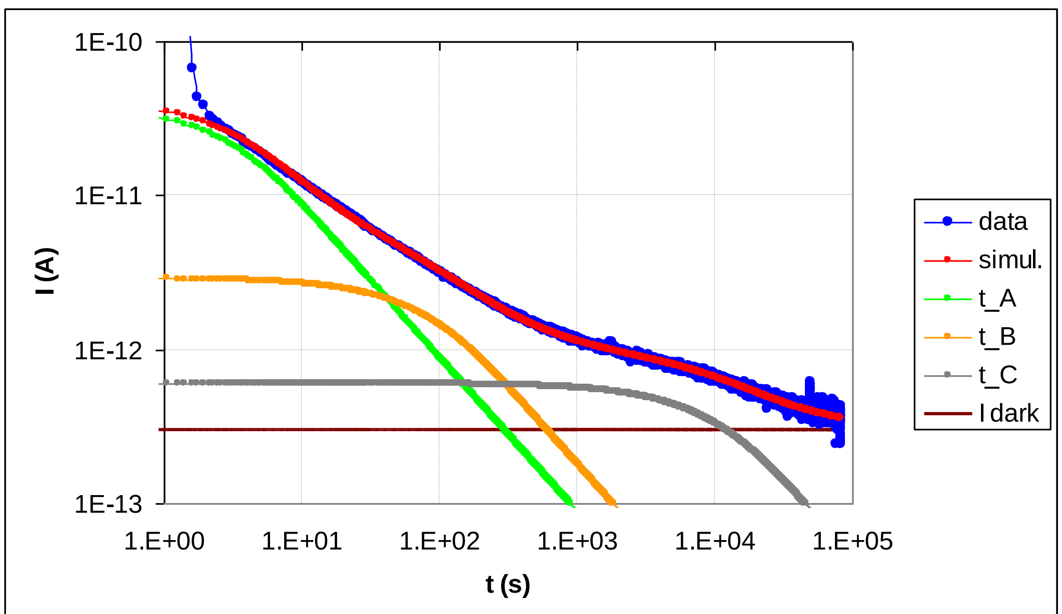
with : $$J_i = \frac{J_\infty}{g\tau_i} kT \frac{dN_i}{dE}$$

Where $\tau_i \equiv \tau^i_{\mathrm{inf}}$.

Persistent Induced Current. Determination of dN/dE and E_{inf}

$$J = J_{\mathrm{dark}} + \sum_{i=1}^{\mathrm{m}} J_i \frac{1 - \exp\left(-\frac{t}{\tau_i}\right)}{t/\tau_i}$$

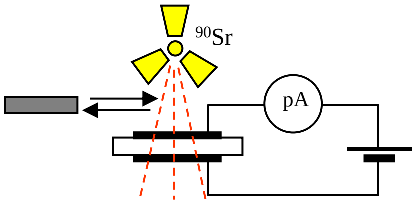
With this expression, m=3 *trap distributions, corresponding to the centres found with the β Radiation Induced Current analysis, can reproduce the observed behaviour of the Persistent current over 5 decades*



In this way, the value of

$$\frac{1}{\tau_{\mathrm{inf}}} = \sigma_t v_p N_V e^{-\frac{E_{\mathrm{inf}}}{kT}}$$

found by the best fit, gives the lower energy E_{inf} of each distribution

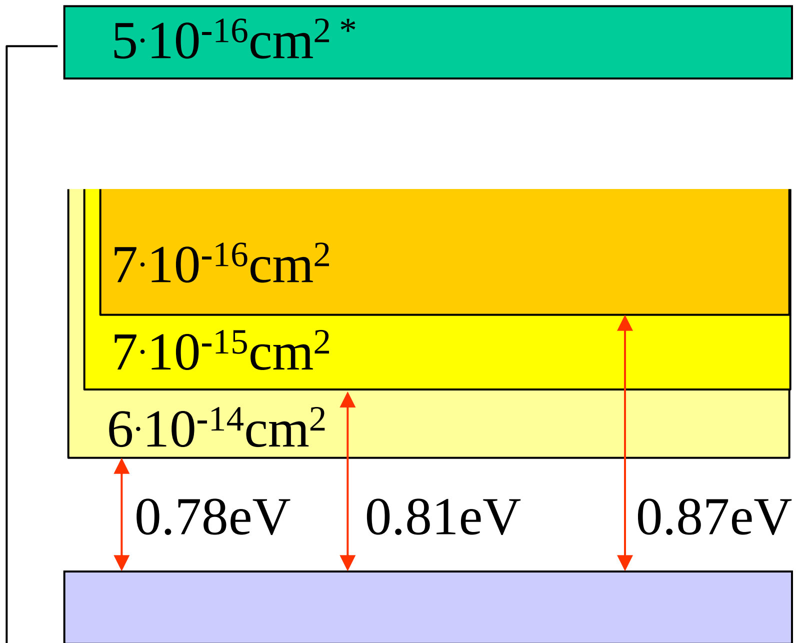


β Radiation Induced Current (βRIC)

Persistent Induced Current (PIC):

Results

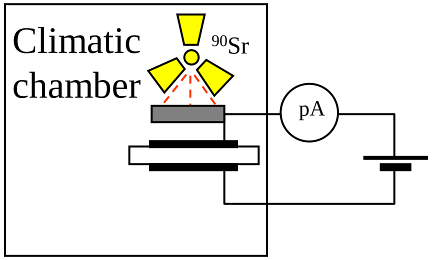
In all the samples under test, we found:



- three defect band distributions, with the same lower limits in all the samples (within 0.01eV)
- the same cross-section values (within 20%)
- the same cross section of the recombination centers (within 50%)

* Good agreement with measurements on natural IIa diamond

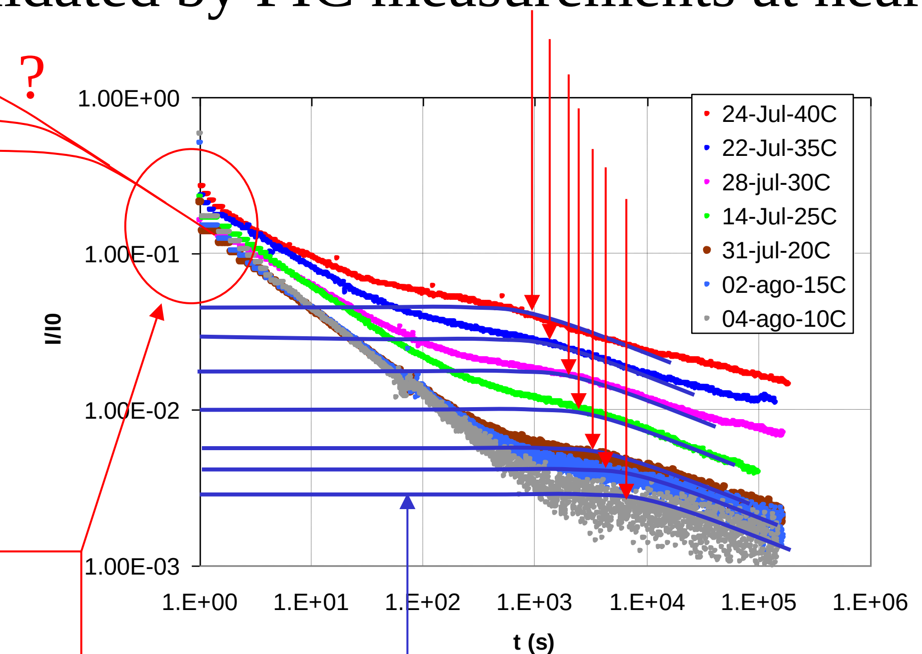
Pan L.S. *et al*, J.Appl.Phys. **73** (6), 15 March 1993 p.2888-2894



Persistent Induced Current (PIC) at near-room temperatures

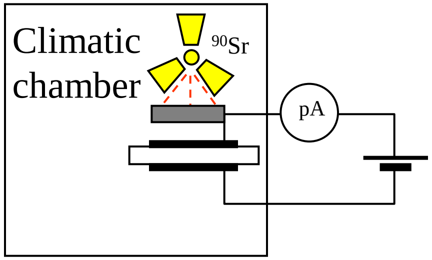
The analysis performed at room temperature combining βRIC and PIC measurements can be validated by PIC measurements at near-room temperatures alone

PIC measurements has been performed on a sample of the batch CDS106 at temperatures between 10°C and 40°C



The shutter time of the β source is too long, at the moment, to see the turning point of the short-lived component of the current

But a dependence on temperature of the intensity and the turning-off time of long-lived component is clearly detectable



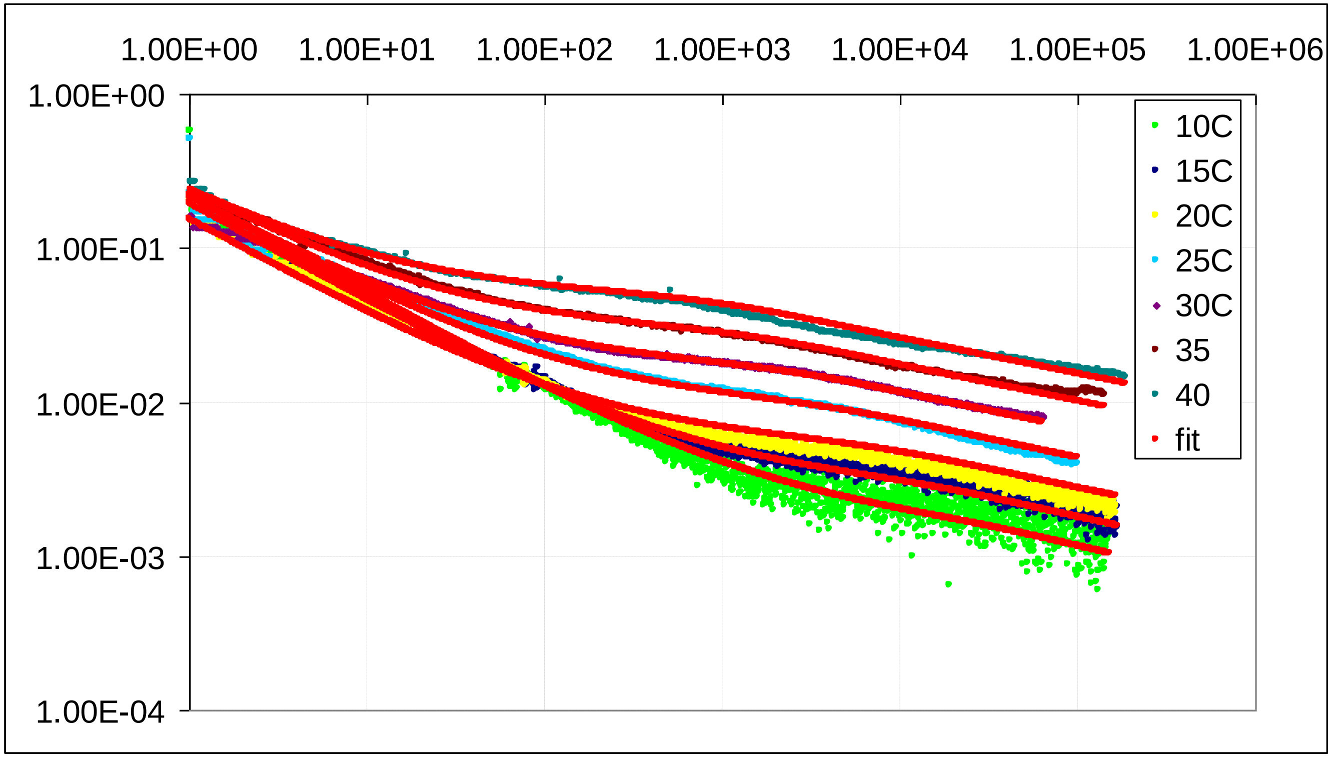
Persistent Induced Current (PIC) at near-room temperatures

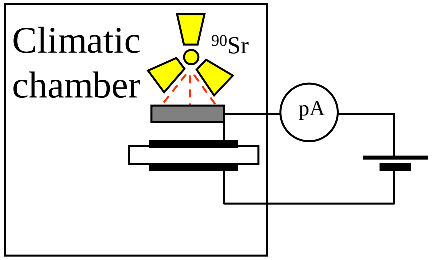
A simultaneous fit of the PIC currents at different temperatures gives a good agreement between theory and experiment:

The fit of the long-lived component of the PIC gives the following values for the deeper trap parameters:

E=0.86 eV

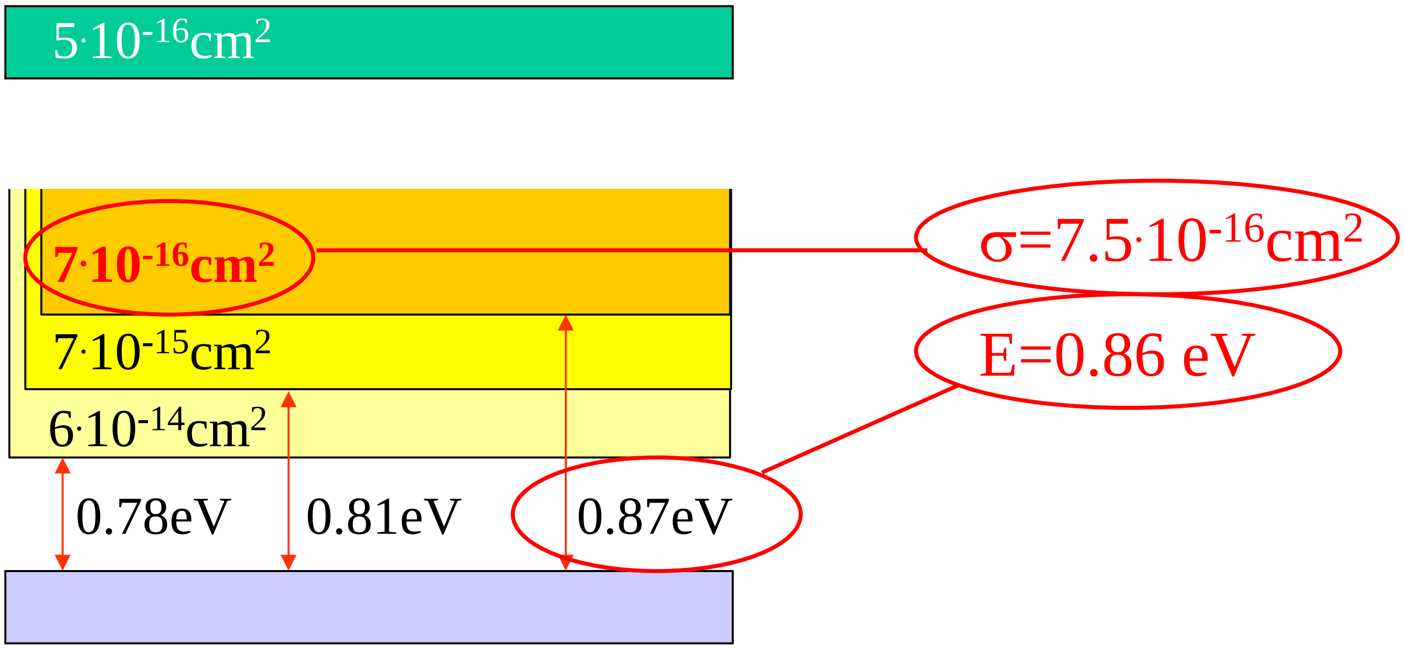
$\sigma=7.5\cdot10^{-16}cm^2$

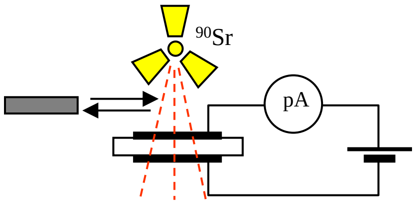




Persistent Induced Current (PIC) at near-room temperatures

Which are, within the experimental errors, exactly the same values obtained with βRIC and PIC analysis at room temperature

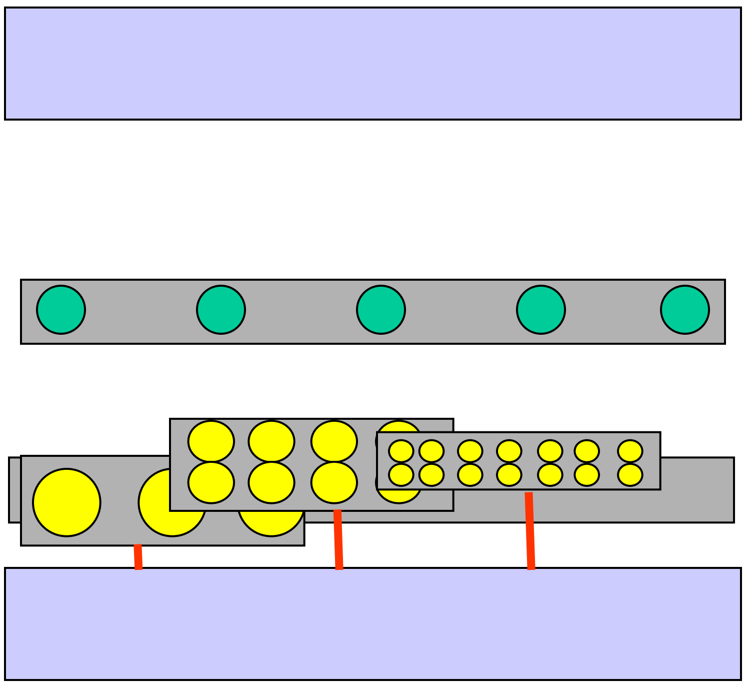




β Radiation Induced Current (βRIC)

Persistent Induced Current (PIC)

Summarizing, βRIC and PIC measurements allows:



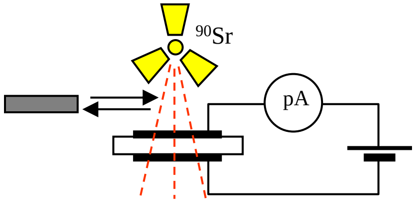
To separate the band “B” in several components of given concentration and capture cross sections

To find the lower energy of each component and the density of level per unit energy

To assign a capture cross section and a concentration to the recombination centers of band “A”

Sample
P13 (1998)

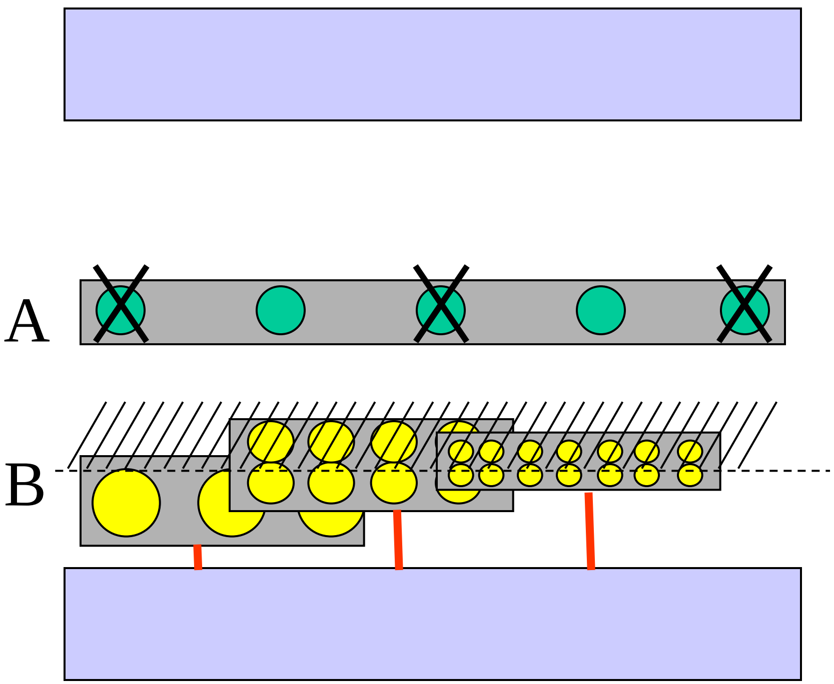
	σ (cm^2)	n (cm^{-3})	ΔE (eV)	dn/dE
B_1	$7 \cdot 10^{-14}$	$6 \cdot 10^{13}$	0.78	$8 \cdot 10^{12}$
B_2	$8 \cdot 10^{-15}$	$3 \cdot 10^{14}$	0.81	$8 \cdot 10^{13}$
B_3	$7 \cdot 10^{-16}$	$5 \cdot 10^{15}$	0.87	$6 \cdot 10^{14}$
A	$5 \cdot 10^{-16}$	$5 \cdot 10^{15}$		



β Radiation Induced Current (βRIC)

Persistent Induced Current (PIC)

RESULTS OF OUR ANALYSIS:

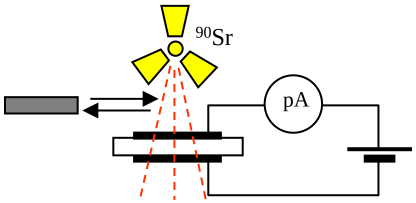


Probably, the diminishing of charged shallow traps is not intrinsic, but related to the lower concentration of recombination centers by compensation

sample P13 (1998)

sample CDS92 P4 (2000)

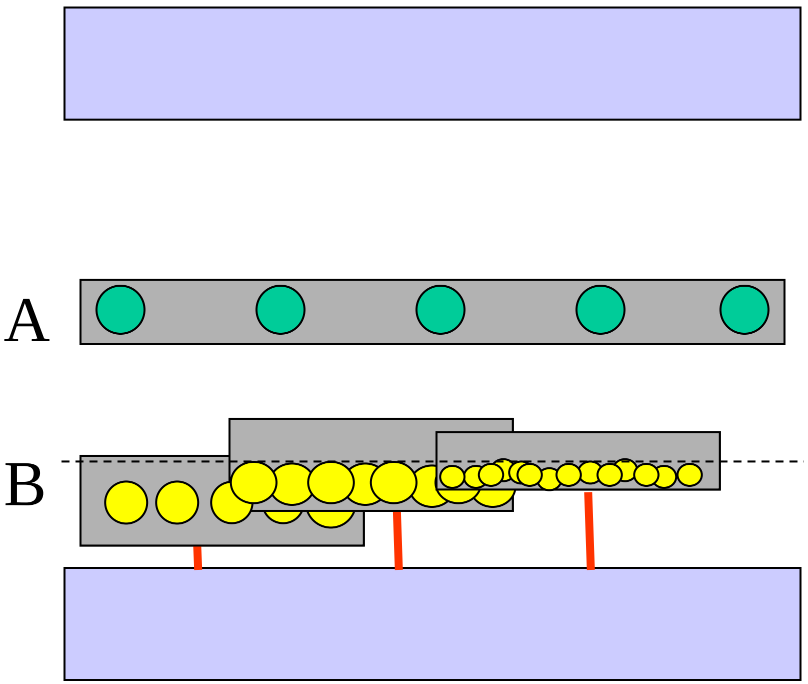
	σ (cm²)	*n* (cm⁻³)	ΔE (eV)	d*n*/dE (cm⁻³eV⁻¹)
B_1	$7\cdot10^{-14}$	$6\cdot10^{13}$ $2\cdot10^{13}$	0.78	$8\cdot10^{12}$
B_2	$8\cdot10^{-15}$	$3\cdot10^{14}$ $4\cdot10^{13}$	0.81	$8\cdot10^{13}$
B_3	$7\cdot10^{-16}$	$5\cdot10^{15}$ $2.5\cdot10^{15}$	0.87	$6\cdot10^{14}$
A	$5\cdot10^{-16}$	$5\cdot10^{15}$ $2.5\cdot10^{15}$		



β Radiation Induced Current (βRIC)

Persistent Induced Current (PIC)

RESULTS OF OUR ANALYSIS:



Campione P13

P16 (neutron irradiated)

Radiation damage by neutron with fluence up to $2 \cdot 10^{15} cm^{-2}$

No effects on recombination centers

General increment of trap level density per unit energy

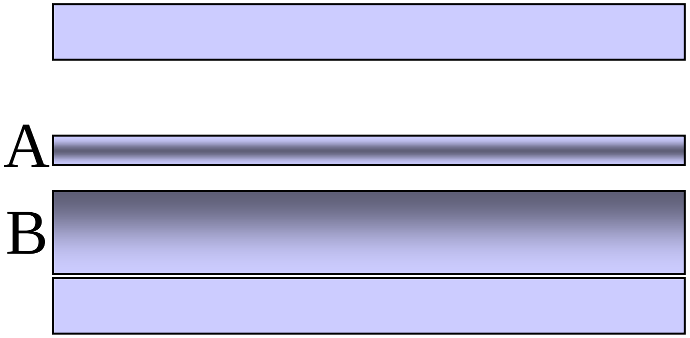
Lowering of the cross section of the low energy tail

	σ (cm^2)	n (cm^{-3})	ΔE (eV)	dn/dE
B_1	$7 \cdot 10^{-14}$ $4 \cdot 10^{-14}$	$6 \cdot 10^{13}$ $2 \cdot 10^{14}$	0.78	$8 \cdot 10^{12}$ $1.5 \cdot 10^{13}$
B_2	$8 \cdot 10^{-15}$	$3 \cdot 10^{14}$ $2 \cdot 10^{14}$	0.81	$8 \cdot 10^{13}$ $1.5 \cdot 10^{14}$
B_3	$7 \cdot 10^{-16}$	$5 \cdot 10^{15}$	0.87	$6 \cdot 10^{14}$ $1.5 \cdot 10^{15}$
A	$5 \cdot 10^{-16}$			

Perspectives

• Investigation of the band-gap level structure of *monocrystallyne* CVD diamond

• A study of shallower trap levels structure and the structure of the recombination “A” distribution:



Modeling of carrier kinetics in pCVD diamond detectors

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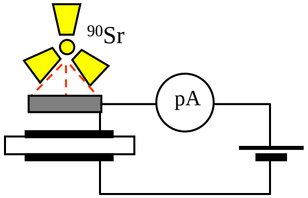
1 INFN and Department of Energetics (Univ. Of Florence)

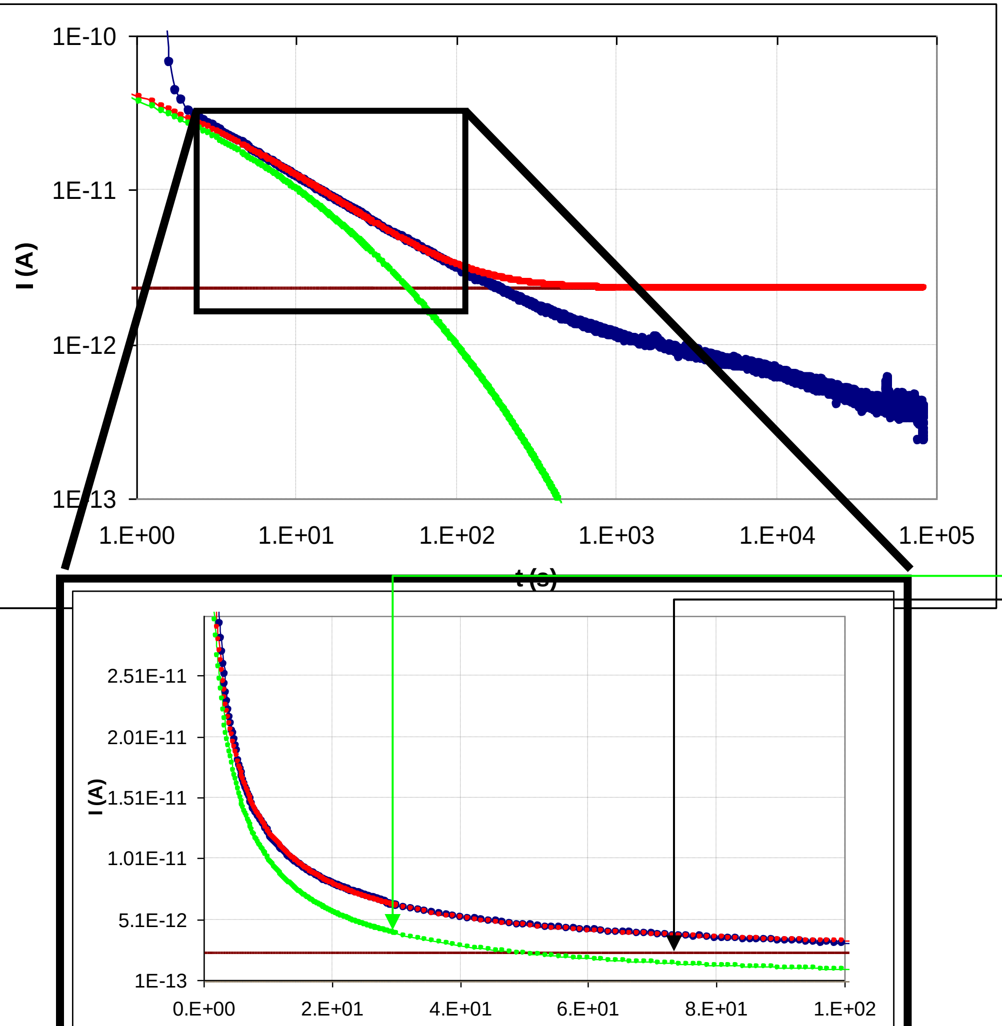
2 INFN and Department of Physics (Univ. Of Florence)

Thank you for listening! ☺



Persistent Induced Current (PIC)

The distributed character of the trap energies is confirmed by measurements of thermal Persistent Induced Currents (PIC)



Usually, the Persistent Photocurrents (PPC) are studied by means of a function called "stretched exponential"

$$i(t) = i_{dark} + i_0 \exp\left\{ -\left(\frac{t}{\tau}\right)^{\gamma} \right\}$$

This function is a phenomenological model whose parameters are not directly related to the trap parameters