Investigation of Damage Induced Defects in Silicon by TCT*

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Abstract

Neutron and ^{60}Co gamma irradiated silicon detectors have been investigated using time resolved current transients (TCT) induced by nanosecond laser pulses. Measurements were performed as function of operating temperature (100 K-300 K) and bias voltage. Illumination was done on both the juntion and ohmic side, allowing the investigation of the free charge carrier transport for electrons respectively holes separately. This way temperature dependent trapping and detrapping effects as well as related electric field transformations have been studied and enable us to extract relevant defect parameters. Results achieved for the damaged detectors will be presented and discussed in comparison with DLTS data.

1. Introduction

Commonly used techniques for defect characterization in silicon are the capacitance- resp. current-deep level transient spectroscopy (C-DLTS, I-DLTS) and the thermally stimulated current method (TSC). They make use of the emission process of captured charge carriers in deep traps as function of temperature resulting in the characteristic properties of the involved defect levels as given by the activation energy, capture cross section and the defect concentration.
The transient current technique (TCT), i.e. the measurement of time resolved current pulse shapes in silicon detectors induced by laser light pulses of subnanosecond duration as function of the sample temperature, is an additional but quite different tool for the characterization of defects. The experimental setup, first results and analysis derived for neutron and gamma irradiated detectors will be presented and discussed in the following sections.

2. Experimental setup

For our experiments ion implanted p^+nn^+ silicon detectors fabricated at the Brookhaven National Laboratory respectively the semiconductor laboratory of the MPI-Munich from high resistivity material (3 kΩcm) have been used. On both the p^+ and the n^+ side a hole of 2mm diameter was left in the Al metallization layer for light injection. The used TCT-setup is quite similar to that descibed in [1,2]. The samples were mounted in a temperature controlled liquid nitrogen cryostat equipped with two optical fiber cables allowing the injection of laser light on both the p^+- and the n^+-side. The current signals are transmitted to a 1 GHz sampling oscilloscope (Tektronix TDS540). The wave length of the used laser diode is 830 nm and pulse durations of less than 1 ns could be achieved.
The neutron irradiations were performed at the Lowel University using the ^{7}Li(p,n) reaction [3] and for the gamma irradiation the ^{60}Co source at the BNL was used.

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3. Experimental results and discussion

Laser induced current pulse shapes have been measured as function of operating temperature and for illuminations on both the p^+ and the n^+ side. This way time resolved electron and hole transport phenomena could be investigated separately. The measured transients were compared with simulated pulse shapes taking into account the initial free charge carrier distribution generated by the laser light, the dependence of the carrier drift velocity on the field strength and temperature and the influence of the electronic circuit on the detector signal [4]. Fitting simulated pulse shapes to measured pulses one gets the effective space charge density as long as the influence of trapping and detrapping of free charge carriers during the collection time on the pulse shape is negligible. As an example, in Fig. 1 measured and simulated current transients as function of temperature are demonstrated for n^+-illumination of a detector after irradiation with an equivalent 1 MeV neutron fluence of 2.5×10^{13} cm^{-2}. In this case the pulse shapes are dominated by the transport of holes while the electron component causes only the small overshoot in the measured transients. With decreasing temperature the pulse width becomes shorter due to an increase of the corresponding drift velocities. On the other hand the shape of the current transients changes with temperature. The slope of the hole current flattens out in the temperature range between 220-170 K and at lower temperatures the slope becomes positive. This development can be explained by hole trapping due to holes created by the injection of laser light themselves. The increase of hole trapping with decreasing temperature leads at first to a compensation of the initially negative space charge and afterwards below a certain temperature the sign of the space charge inverts from negative to positive. It should be mentioned that the transients presented in Fig.1 were allways measured under steady state conditions with respect to the trapping induced change of the space charge density (see below).

These space charge transformation effects can be described by trapping and detrapping processes of laser induced free charge carriers. For simplicity we consider capture and emission processes of holes only as observed by n^+-illumination (see Fig. 1). At low temperatures the concentration of holes in the space charge region of the detector is dominated by laser injection and can be regarded as constant as far as the effective time constant responsible for the change of the space charge is long compared with the repetition rate of the laser. Furthermore, we suppose that the space charge density stays homogeneously distributed throughout the detector volume all the time. This assumption is supported by the fact that the measured transients can be reproduced with high precision by using a linear graded field distribution in the simulations.
With these conditions the rate equation for the density of trapped holes p_t is given by:

$$dp_t / dt = c_p p(P_t - p_t) - e_p p_t \qquad (1)$$

where p is the concentration of holes, P_t the concentration of traps, c_p the capture coefficient and e_p the emission rate for holes. c_p is given by $c_p = \sigma_p v_{th,p}$ with the capture cross section σ_p and the thermal velocity of holes $v_{th,p}$. The emission rate e_p depends strongly on the temperature as given by $e_p = c_p N_V exp(-\Delta E_t / k_B T)$. Here N_V is the density of states in the valance band, ΔE_t the ionization energy of the trap level and k_B the Boltzmann constant.
The analytical solution of eq. (1) can be written as:

$$p_t(t) = c_p p P_t \tau_{eff,p} \left\{1 - \exp(-t / \tau_{eff,p})\right\} \qquad (2)$$

with

$$\tau_{eff,p} = \left(c_p + e_p\right)^{-1} \qquad (3)$$

which desribes the effective time constant for trapped holes caused by the competing capture and emission processes. Taking the saturation level $p_{t,\max} = p_t(t \to \infty)$ the effective total space charge density at temperature T in steady state conditions is given by:

$$q_0 N_{eff}(T) = q_0 N_{eff,0} + q_0 p_{t,\max}(T) \qquad (4)$$

where $q_0 N_{eff,0}$ represents the effective space charge density at room temperature (RT). This relation holds only if the hole trap is considered to be in the unoccupied state at RT. A more detailed description of the model can be found in Ref. [4].
An analysis of all measured transients as function of temperature by the simulation procedure mentioned above results in $N_{eff}(T)$ and using eq.(4) $p_{t,\max}(T)$ for hole traps respectively $n_{t,max}(T)$ for electron traps could be extracted. These quantities are shown in Fig. 2 as function of temperature for a neutron irradiated sample (Fig. 2(a) p^+-illumination, Fig. 2(b) n^+-illumination) and a detector after exposure to ^{60}Co gamma radiation (Fig. 2(c) n^+-illumination). The observed temperature dependence of $p_{t,max}(T)$ and $n_{t,max}(T)$ for the neutron damaged device can only be reproduced if two different defect levels are taken into account. The corresponding curves are included in Fig. 2(a,b). For the gamma irradiated sample the experimental data can be fitted by assuming a single trap level with an activation energy of 0.54 eV. According to eq. (2) and (3) $p_{t,\max}(T)$ is independent on the capture coefficient c_p and, therefore, no information on the capture cross section can be achieved. Thus, the dynamic process as described by eq. (2) has to be measured e. g. by recording transients after illumination for various periods of time. Such dependence of current transients on the filling time is shown in Fig. 3 for a neutron damaged device. From these measurements $p_t(t,T)$ can be achieved and from a plot of $\ln\{(p_{t,\max}(T) - p_t(t,T))/p_{t,\max}(T)\}$ versus the filling time (see Fig. 4) the time constant $\tau_{t,eff}$ respectively the capture cross section could be extracted. The extracted level parameters ΔE_t, σ_t and introduction rates g_t are summerized in Table 1 and compared with DLTS data reported in Ref. [5].
The observed hole trap with an activation energy of 0.36 eV is well known from DLTS studies of neutron and gamma irradiated silicon diodes and is attributed to the C_iO_i complex. The electron trap level at E_C -0.42 eV observed with TCT is a supperposition of two levels at E_C -0.39 eV and E_C - 0.42 eV which could be separated by a detailed analysis of DLTS measurements [5,6]. Both deep defect levels at $E_C - 0.52$ eV and $E_V + 0.51$ eV in the neutron damaged sample were so far not observed by DLTS in n-type devices. But in p-type silicon the hole trap level was detected by DLTS after neutron irradiation showing nearely identical values not only for the ionization energy and capture cross section but also for the introduction rate. Wether the hole trap at $E_V + 0.54$ eV in the gamma irradiated detector corresponds to the defect level in the neutron damaged device has to be proven by complementary DLTS studies.

4. Conclusions

It is demonstrated that the TCT-methode is a further powerfull tool for investigations of radiation induced defect levels in high resistivity silicon. Due to the possible illumination of both the p^+- and the n^+ - side the characteristic parameters of electron and hole traps can be measured separately. The experimental results have shown that especially very deep levels close to mid band gap can be detected with high sensitivity.
Further investigations on detectors irradiated with different neutron and gamma fluences, improvements of the experimental techniques and of the data analysis have to be undertaken to get more insight in the dynamic processes and the involved defect levels.

References

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List of Tables:

Table 1: Comparison of defect level parameters ΔE_t , σ_t and introduction rates g_t extracted from TCT and DLTS measurements.

Irrad.	Trap	TCT			DLTS			Defect
		ΔE_t (eV)	σ_t (cm^{-2})	g_t (cm^{-1})	ΔE_t (eV)	σ_t (cm^{-2})	g_t (cm^{-1})	
Neutron	Electron	0.42	--	1.7	0.39	1×10^{-15}	0.4	unknown
					0.42	1×10^{-15}	0.8	VV(-/0)
Neutron	Electron	0.52	--	0.03	--	--	--	unknown
Neutron	Hole	0.36	1.2×10^{-15}	1.1	0.36	1.2×10^{-15}	1.2	CO(0/+)
Neutron	Hole	0.51	9.8×10^{-15}	0.04	0.51	1×10^{-14}	0.06	unknown
$^{60}Co\ \gamma$	Hole	0.54	--	3000*)	--	--	--	unknown

*) introduction rate given in ($cm^{-3}rad^{-1}$)

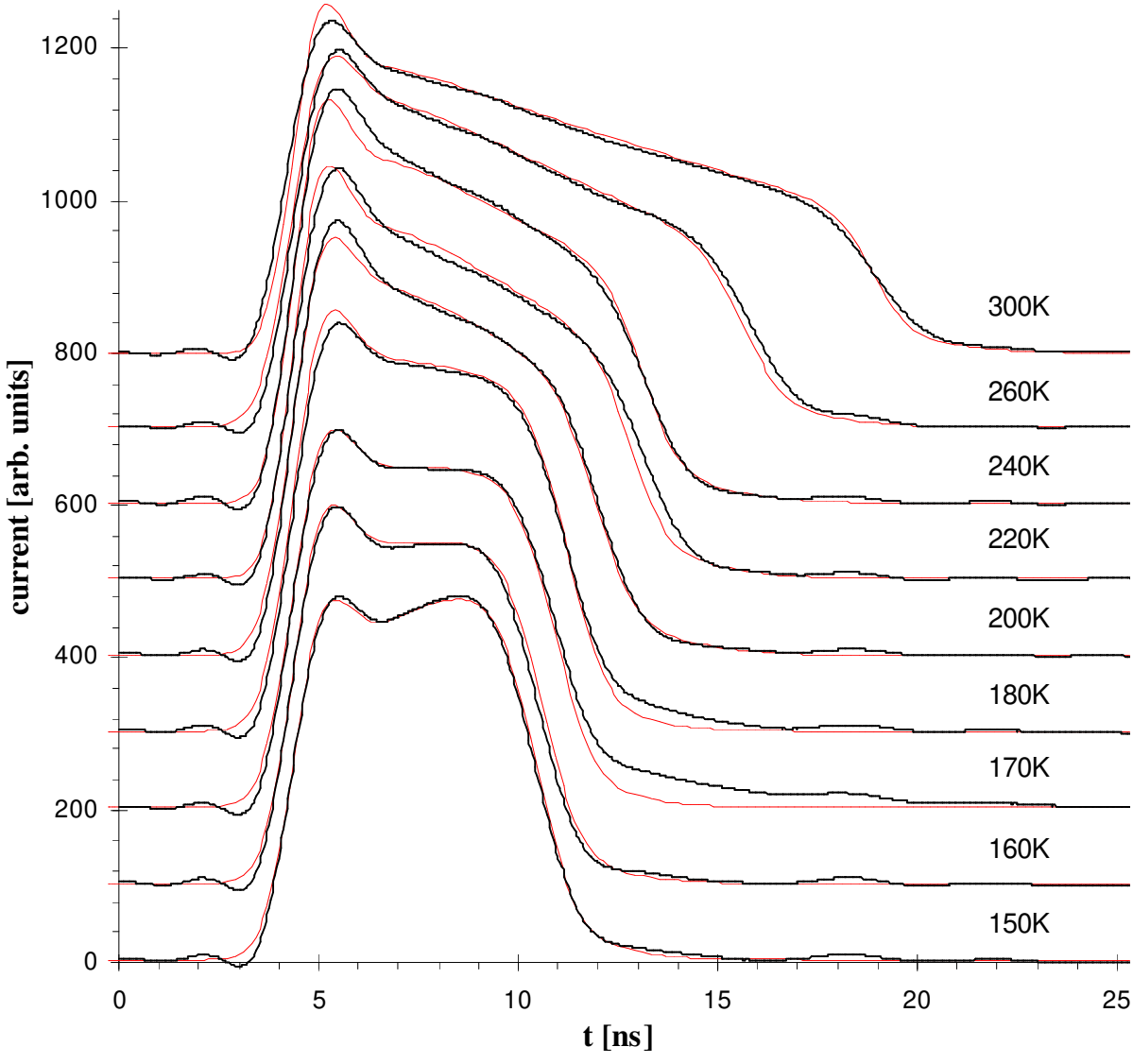
Figure captions:

Fig. 1: Comparison of measured (thick lines) and simulated (thin lines) current transients as function of temperature for n^+-illumination ($\Phi_{eq} = 2.5\times10^{13}$ cm^{-2} , f = 100 Hz, V_B=150 V).

Fig 2: Temparature dependence of the concentration of trapped charge carriers: (a) trapped electrons $n_{t,max}$ after neutron damage, (b) trapped holes $p_{t,max}$ after neutron damage and (c) trapped holes $p_{t,max}$ after gamma irradiation.

Fig. 3: Effect of laser filling time on current transients ($\Phi_{eq} = 2.5\times10^{13}$ cm^{-2}, n^+-illumination, f=100 Hz, T=160 K, V_B=150 V).

Fig. 4: Fraction of trapped holes $(p_{t,max}(T)-p_t(t,T))/ p_{t,max}(T)$ as function of filling time at different temperatures ($\Phi_{eq} = 2.5\times10^{13}$ cm^{-2}, n^+-illumination, f=100 Hz, V_B=150 V).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170K
160K
150K

Fig. 1

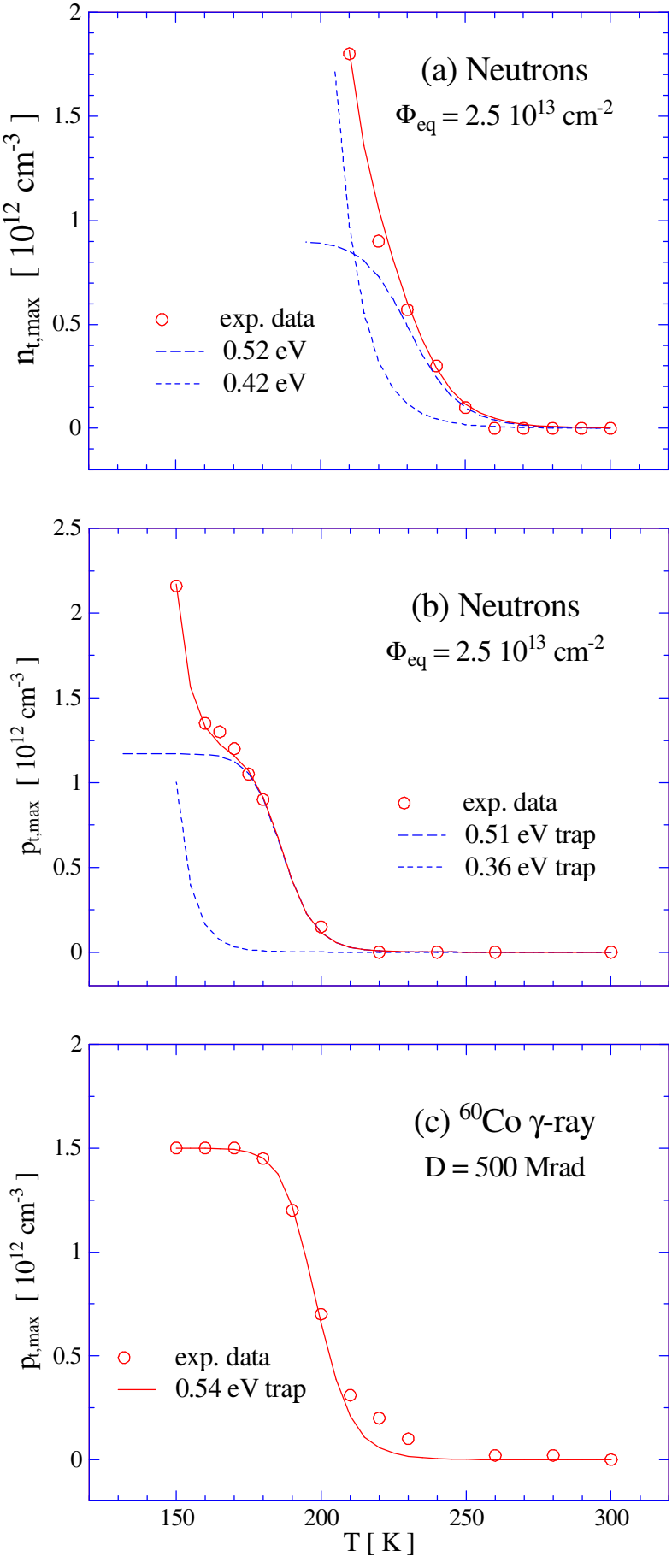
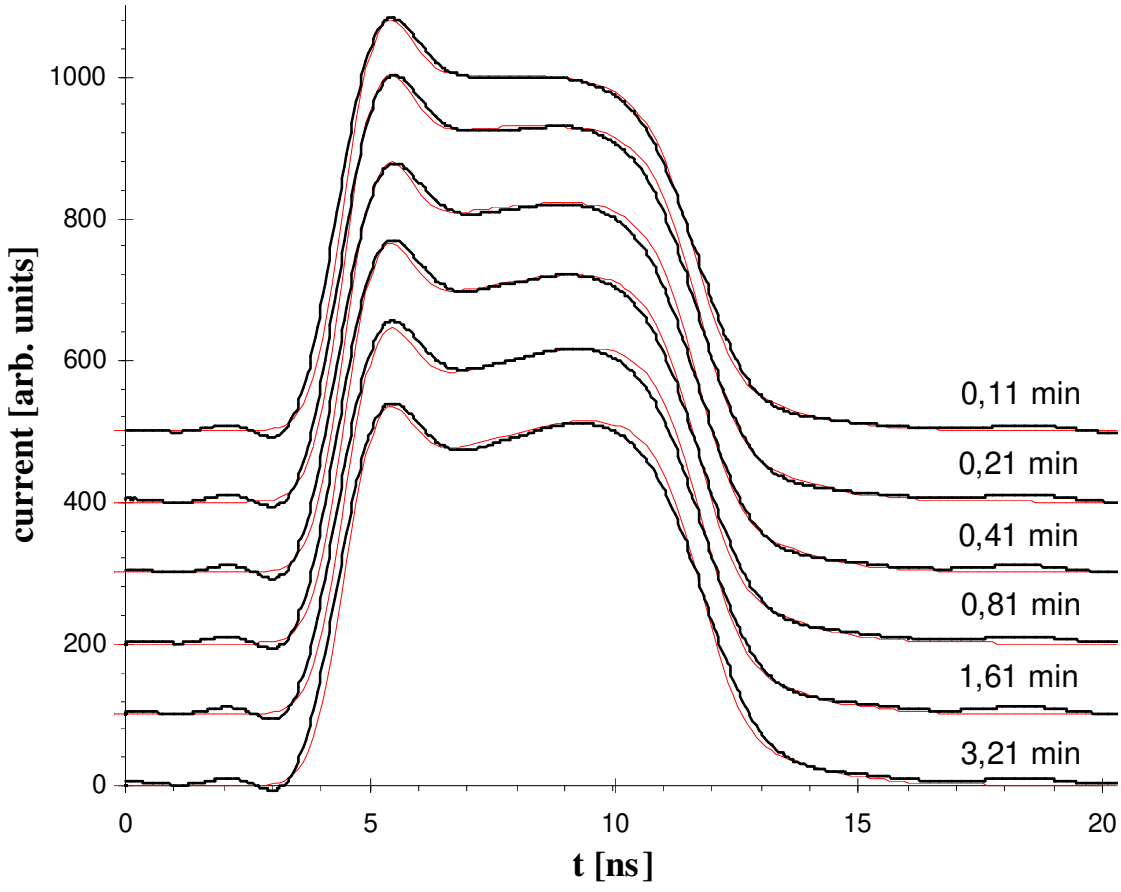

(a) Neutrons
Φ_{eq} = 2.5 10^{13} cm^{-2}
exp. data
0.52 eV
0.42 eV
$n_{t,max}$ [10^{12} cm^{-3}]
(b) Neutrons
Φ_{eq} = 2.5 10^{13} cm^{-2}
exp. data
0.51 eV trap
0.36 eV trap
$p_{t,max}$ [10^{12} cm^{-3}]
(c) ^{60}Co γ-ray
D = 500 Mrad
exp. data
0.54 eV trap
$p_{t,max}$ [10^{12} cm^{-3}]
T [K]

Fig. 2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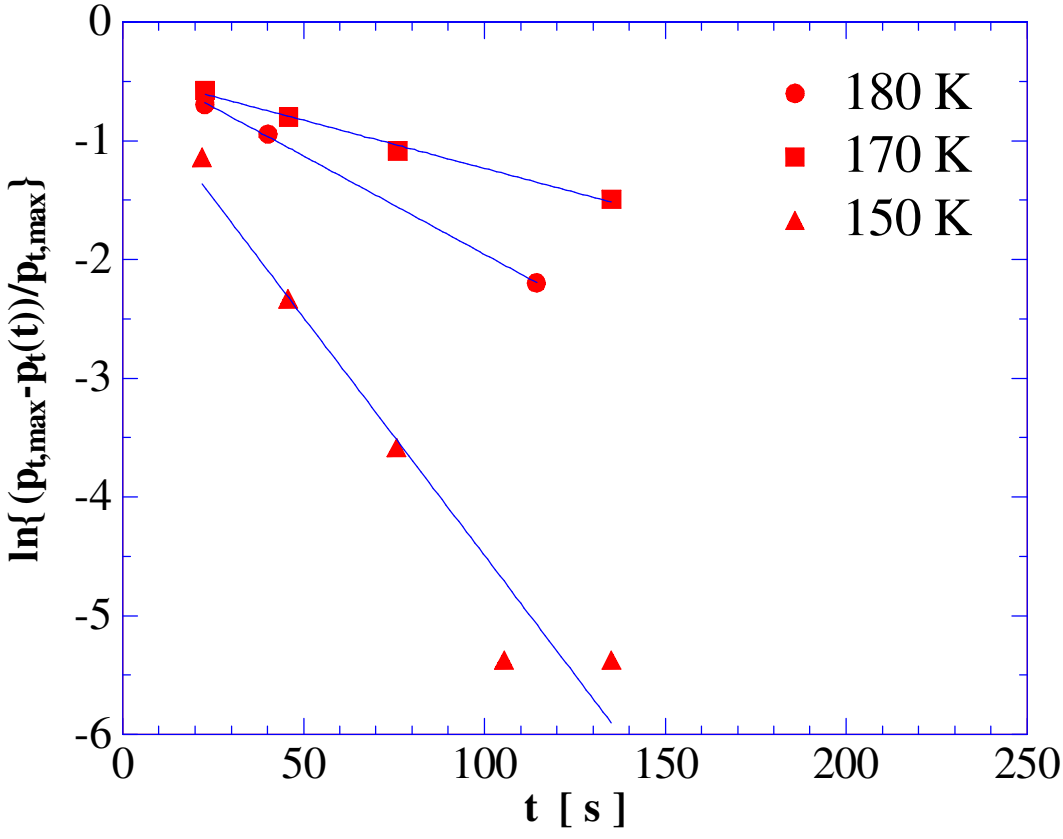
3,21 min

Fig. 3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170 K
150 K

Fig. 4