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TOSCA simulation of some effects observed in irradiated silicon detectors

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Abstract

TOSCA package has been used to simulate some effects observed recently in heavily irradiated silicon detectors. In particular, unexpected possibility of α-particle registration at p+ contact has been explained without presented elsewhere assumption that there was p-n junction of unknown origin beneath p+ layer. Performed simulations showed that assumption on relaxation-like character of irradiated silicon material is also not necessary to explain such effects like low-voltage capacitance peak in reverse bias and negative capacitance in forward bias.

1 Introduction

Intensive studies on heavily irradiated silicon detectors and test diodes have been performed in recent years. Some new effects have been discovered and described [3-7]. A great effort is still needed to understand the behaviour of irradiated silicon. The TOSCA simulations presented in this article should help in it.

One of most interesting effects is recently reported [4,8] a possibility of registration of α-particle signals when illuminating p+ side of inverted silicon diode (detector) at bias voltages well below depletion voltage. Authors have come to conclusion that there should be p-n junction beneath p+ layer responsible for this effect. This assumption seems to be not valid. Described effect could be explained in another way.

From the macroscopic point of view, heavily irradiated silicon is an almost intrinsic material. The four-probe resistivity measurements show values of $10^4 - 10^5\Omega$cm in as-irradiated silicon [2]. Similar values could be estimated from IV measurements on forward biased diodes [6,7]. On the other hand there is high density of traps of various kind introduced by irradiation. The trap levels are fully or partially filled in such way that they compensate charges of shallow donors and acceptors in the absence of external polarization.

There is also an evidence [1,8] that voltage applied to n+ - p junction simultaneously depletes charged trap levels. These levels could be detected as steps on C(f) curve for bias voltages smaller than depletion voltage. In fact, depletion voltage should be defined for each kind of trap but usually that term is used to describe dominant trap with highest density. In the case of heavily irradiated silicon it is acceptor-like trap with density of about $10^{12}cm^{-3}$.

It seems to be justified to make the assumption that in heavily irradiated silicon exist one acceptor-like trap with density smaller than $10^{11}cm^{-3}$ as minimum. This assumption allows to conclude that even at bias of few volts, weak electric field reaches p+ layer of diode (detector). This field meets strong, shallow electric field existing at p+ layer as result of gradient of dopant concentration. Under these circumstances a quite effective collection of charge deposited by α-particles illuminating p+ side of diode is possible. TOSCA simulations have been done with above assumptions. The results are presented in the second section.

In the third section the diode model for TOSCA has been "biased" in forward direction. Results of preliminary simulations presented here could help to understand why registration of ionizing particles is possible in forward biasing [3,6] of irradiated diodes.

The description of heavily irradiated silicon as relaxation-like material has been proposed recently [7]. The definition of relaxation-like material presented in this paper requires the value of carrier lifetime $\tau_{e,h} \ll \tau_D$ where τ_D is dielectric relaxation time $\tau_D = \rho\epsilon\epsilon_0$. For maximum value of silicon resistivity $\rho \approx 10^5\Omega$cm in room temperature, the maximum possible value of τ_D reaches 10^{-7}s.

There is also statement presented in this paper that such effects as low-voltage capacitance peak in reverse bias and negative capacitance in forward bias cannot be explained by lifetime theory. Simple TOSCA simulations presented in fourth section for $\tau_{e,h} \geq \tau_D$ showed that the statement mentioned above is not valid.

2 Simulation of p+ side illumination by α-particles

For all simulations presented in this article simple model of silicon diode was used (figure 1).

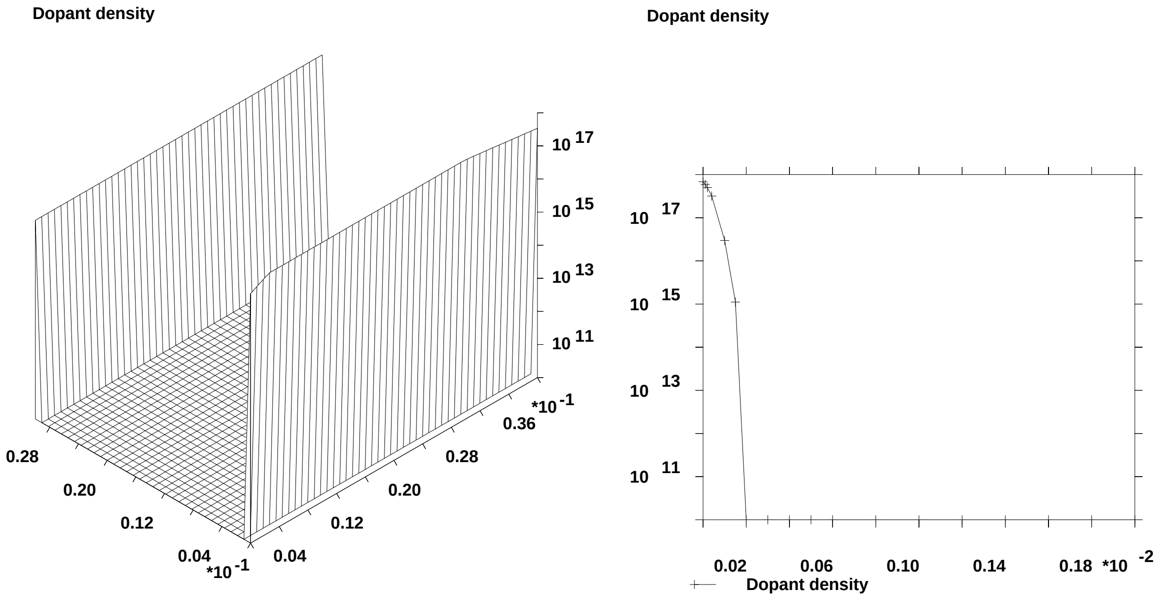


Figure 1: Dopant density (1/cm3) in diode model volume and in p+ layer (all dimensions in cm)

It was assumed that acceptor density in bulk Na $= 2 \cdot 10^{10} cm^{-3}$ and that maximum dopant density in p+ and n+ layers was Nmax $= 1 \cdot 10^{18} cm^{-3}$. Technological thickness of p+ and n+ layers were about 2μm and 1μm respectively. Diode width was 400μm, length = 1cm and thickness 300μm. X - coordinate laying in "surface" plane of diode had x = 0 at the edge of the diode, y - coordinate, perpendicular to the "surface" had y = 0 at p+ side of diode. It was also assumed for all simulations that temperature T = 295°K.

For simulations presented in this section it was assumed that carrier lifetime $\tau_{e,h} = 10^{-7}$s and that single α-particle created in diode volume total charge of about 10^{-12}C.

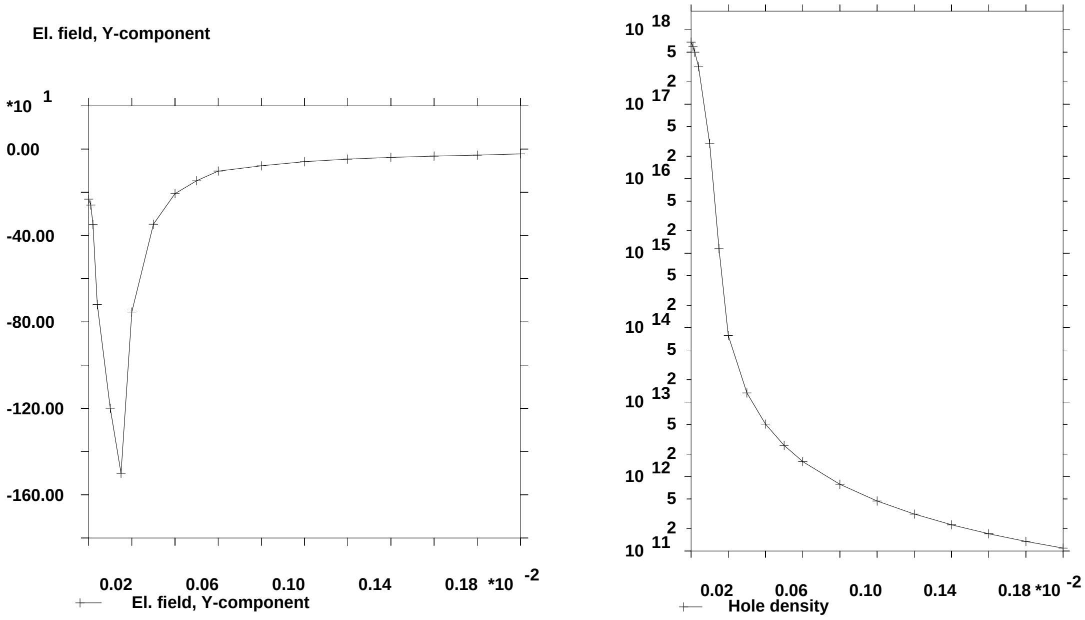


Figure 2: Electric field (V/cm) and hole density (1/cm3) at p+ layer for Ubias=0V, (horizontal axes in cm)

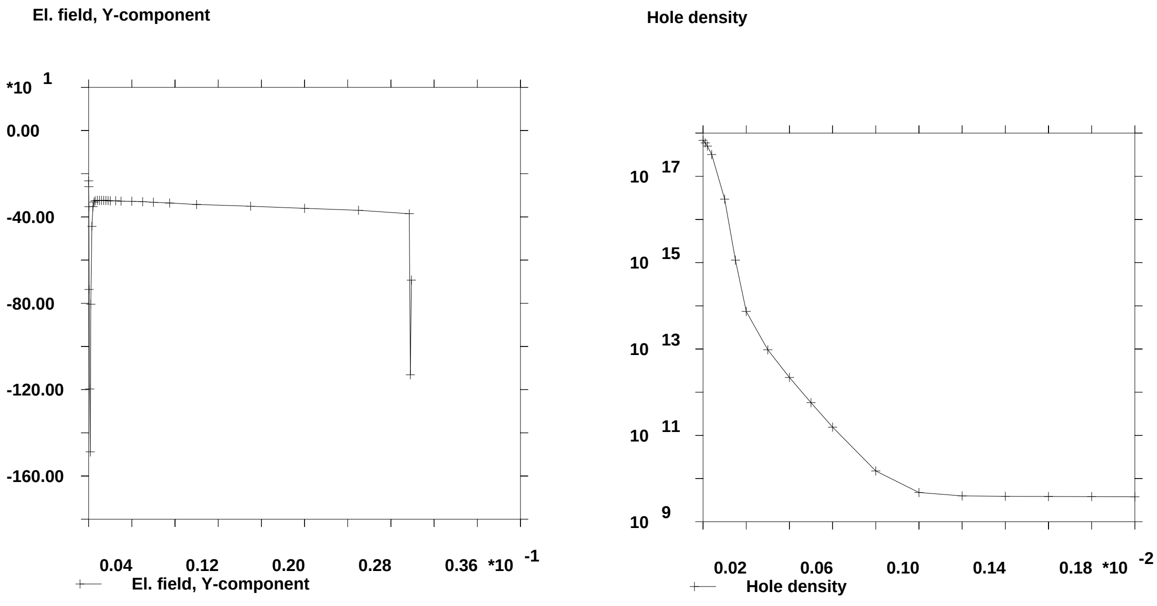


Figure 3: Electric field (V/cm) in whole diode and hole density (1/cm3) at p+ layer for Ubias=10V, (horizontal axes in cm)

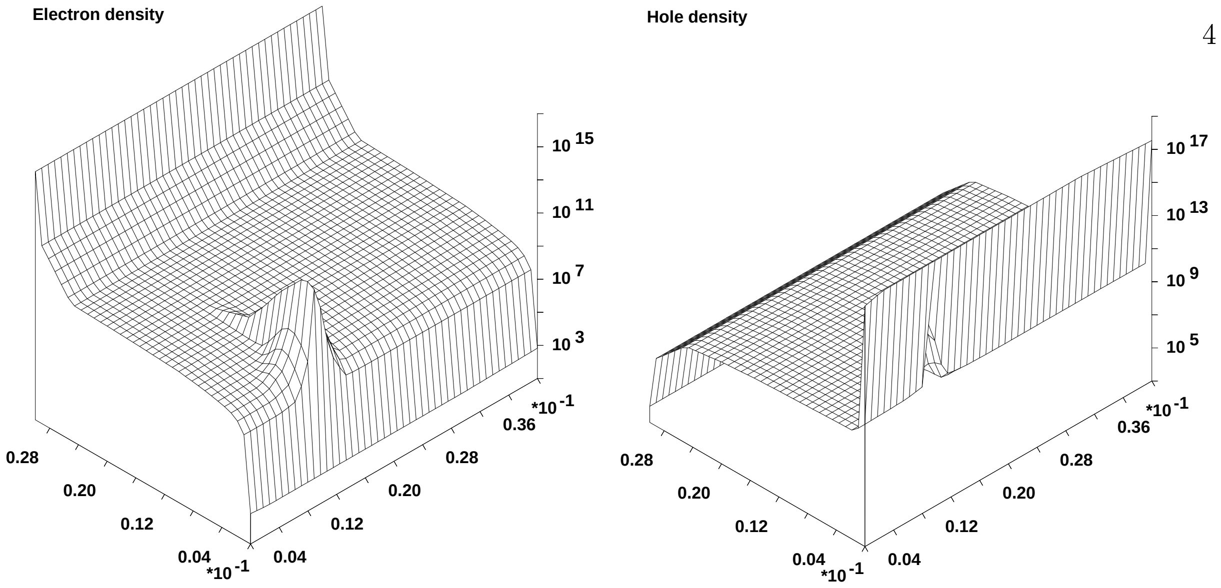


Figure 4: Electron and hole densities (1/cm3) in diode model volume, 1ns after alpha particle impact

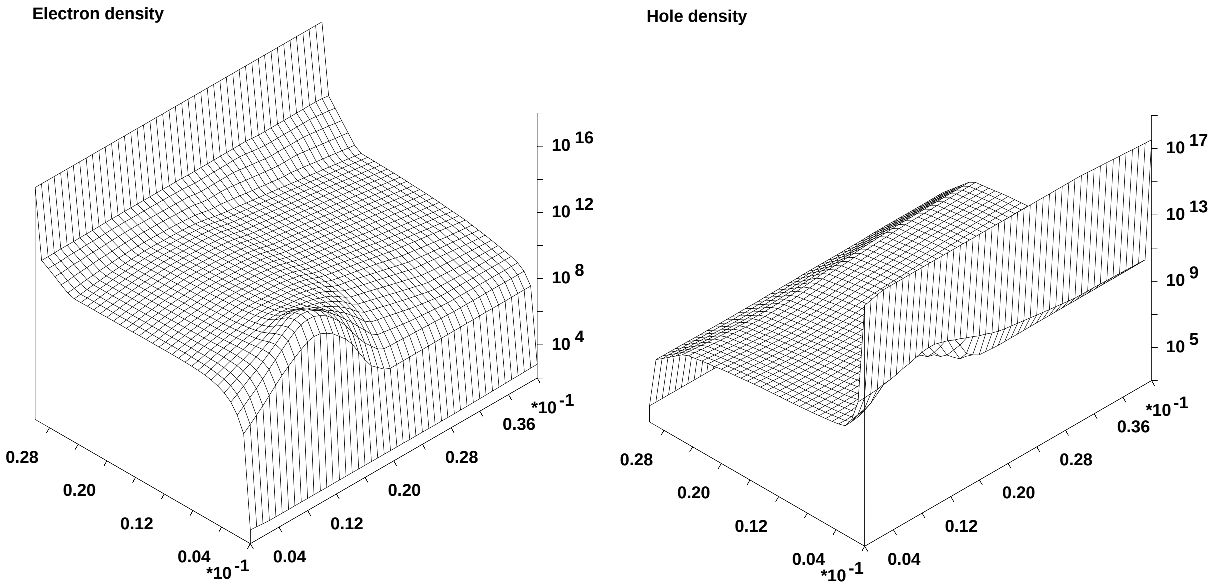


Figure 5: Electron and hole densities (1/cm3) in diode model volume, 25ns after alpha particle impact

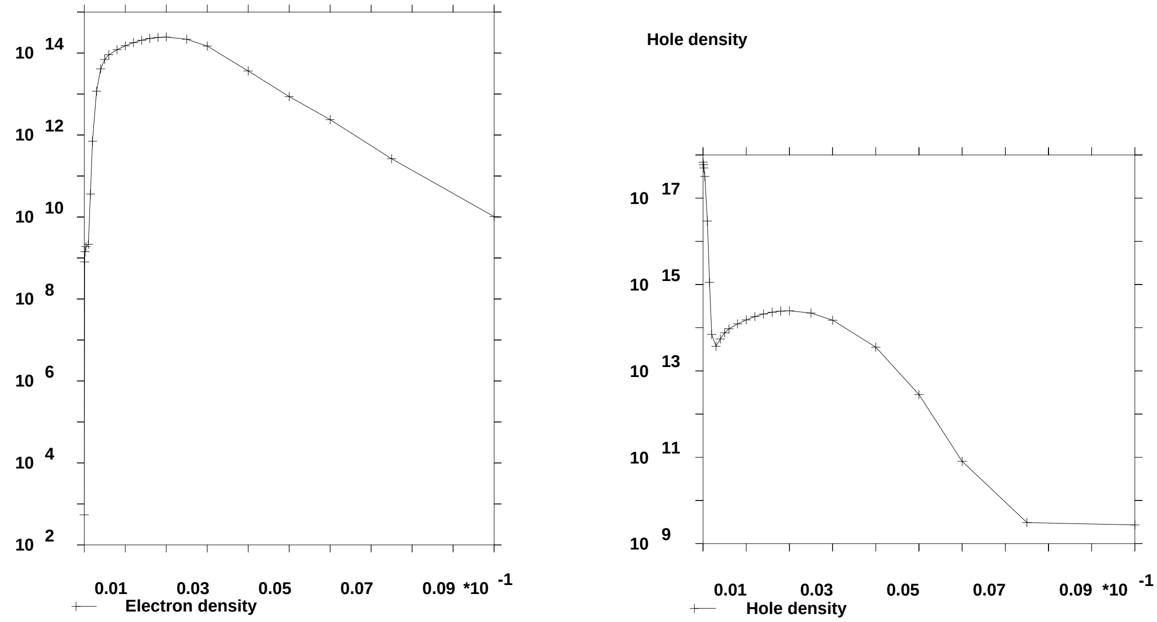


Figure 6: Electron and hole densities (1/cm3) at p+ layer of diode model, 1ns after alpha particle impact (cross-section in plane x=100mic., horizontal axes in cm)

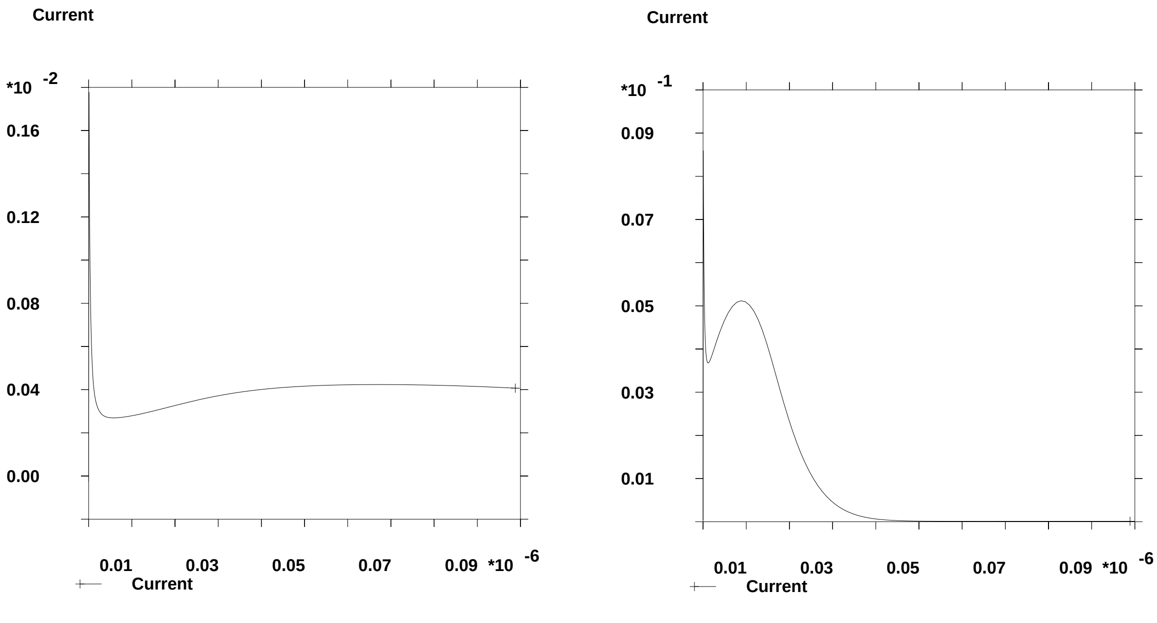


Figure 7: Diode current (A) as function of time (s) for Ubias=10V (left side) and for Ubias=50V (right side)

Maximum of deposited charge was placed at y = 20μm in x = 100μm plane. Charge distribution had symmetric, exponential decay in x and y directions.

Figure 2 shows that a relatively strong internal electric field exists in the vicinity of p+ contact even without external polarization (Ubias = 0V).

The hole distribution for this case is presented in the same figure. One could notice long "tail" in the hole distribution and "deficit" in its maximum concentration in comparison with the acceptor distribution (fig. 1).

Figure 3 shows that at Ubias = 10V (p+ contact was set to zero potential) there is electric field of value higher than 300V/cm along whole diode. In the same figure the hole distribution near p+ layer could be seen (compare with fig. 2).

Figures 4 and 5 present electron and hole distributions 1ns and 25ns after α-particle impact.

The cross-sections of spatial distributions presented in figure 4 could be seen in figure 6. One could see asymmetry in hole and electron distributions created during 1ns drift of carriers in electric field.

Figure 7 shows current pulse shapes for Ubias = 10V and Ubias = 50V.

Table 1 contains values of charge collection efficiency (in percents) calculated for various bias voltages and for two integration periods - 25ns and 100ns.

	time of integr.=25ns	time of integr.=100ns
Ubias in V	Charge coll. eff.	Charge coll. eff.
5	2.7	12.0
10	8.1	38.9
20	28.0	87.4
50	93.1	98.3
100	99.2	99.8

Table 1. Charge collection efficiency in percents

The results of simulations confirm that signals from α-particles illuminating p+ side of heavily irradiated silicon diode could be observed at relatively low bias voltages.

3 Forward biased diode

The diode model described in previous section has been used to simulate possibility of ionizing particle registration with the forward biased diode.

Figures 8 and 9 show electron and hole densities for Ubias = -10V, 1ns after α-particle impact for two values of carrier lifetime.

Figure 10 shows that high recombination rate (low value of carrier lifetime) is necessary to obtain non-zero electric field in the diode volume, and in consequence, effective charge collection.

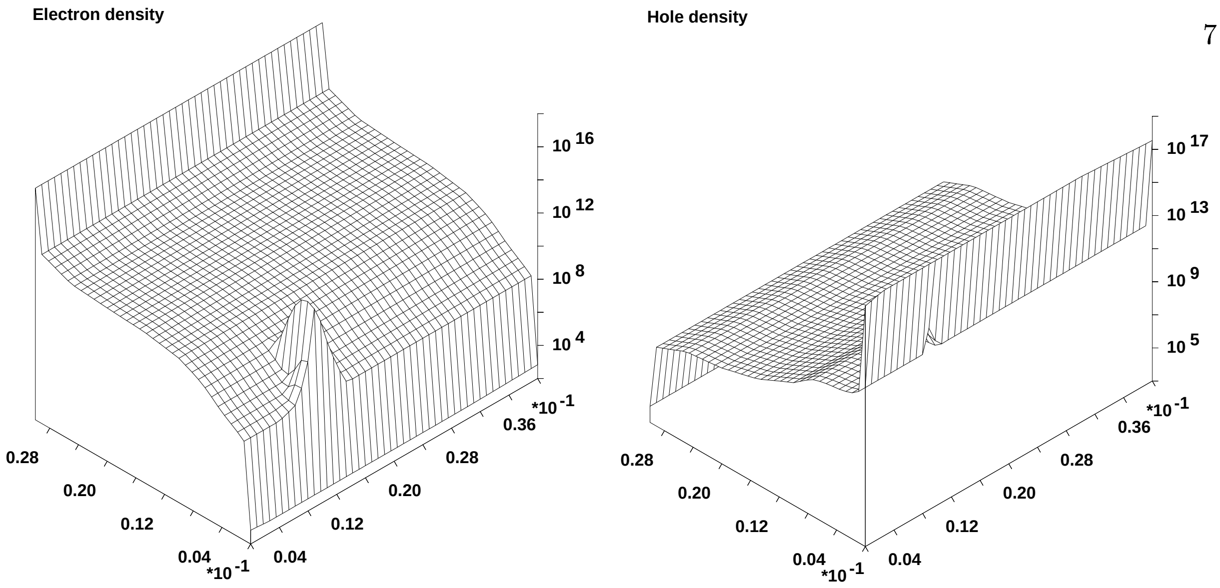


Figure 8: Electron and hole densities (1/cm3) for diode model with $\tau_{e,h} = 10^{-9}$s, 1ns after alpha particle impact. Forward bias = -10V.

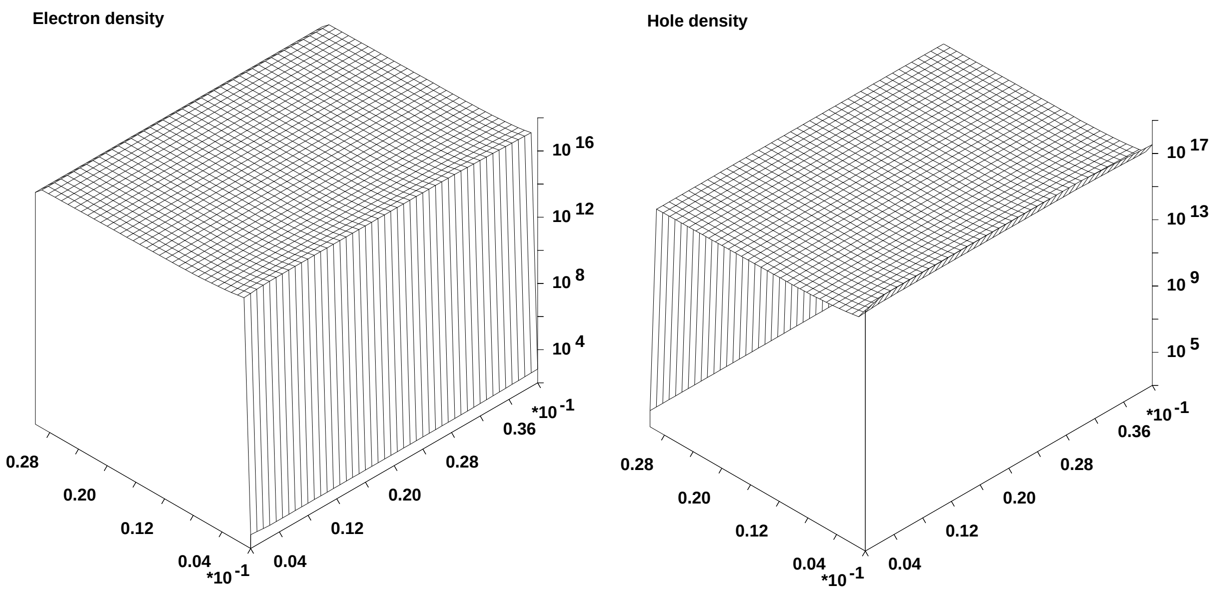
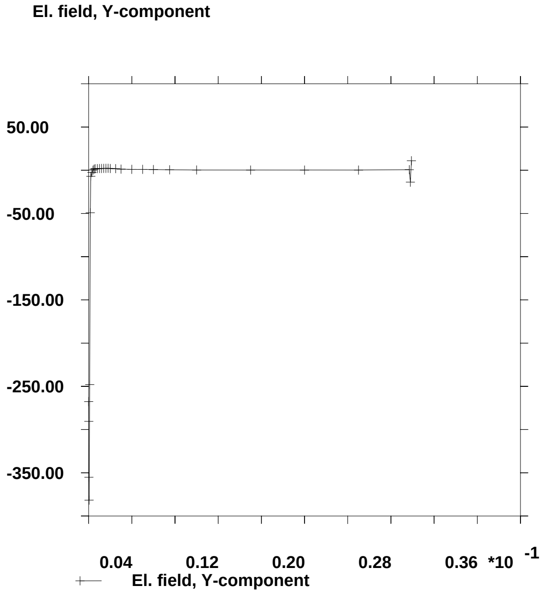


Figure 9: Electron and hole densities (1/cm3) for diode model with $\tau_{e,h} = 10^{-5}$s, 1ns after alpha particle impact. Forward bias = -10V.



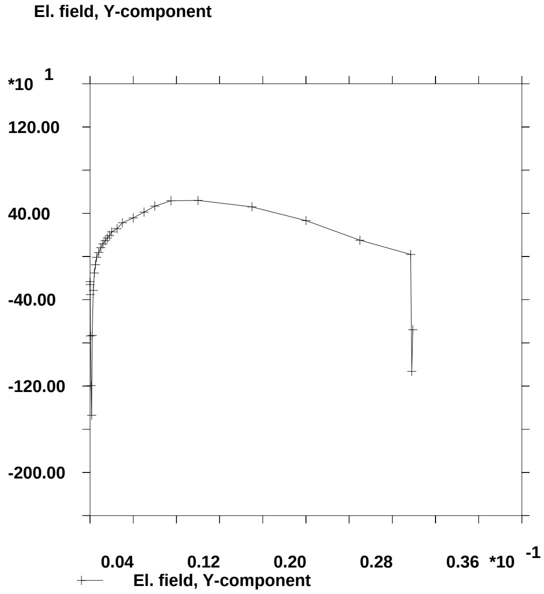


Figure 10: Electric field (V/cm) in diode model with $\tau_{e,h} = 10^{-5}$s (on left) and for diode model with $\tau_{e,h} = 10^{-9}$s (on right). Forward bias = -10V in both cases (horizontal axes in cm).

4 Simulation of diode capacitance

The calculations of values of diode capacitance have been performed for previously described model (zero-potential has been set for n+ contact what results now in negative values of reverse bias). Calculations have been performed for the wide range of bulk acceptor concentrations ($10^{10}-10^{13}cm^{-3}$), wide range of carrier lifetimes ($10^{-2} - 10^{-9}$s) and measurement frequencies ($10^2 - 10^9$Hz).

For each case TOSCA has given negative values of diode capacitance above certain small value of forward bias.

For carrier lifetimes smaller than 10^{-5}s and acceptor bulk concentrations higher than $10^{11}cm^{-3}$ calculated C(Ubias) curves showed maximum for bias voltages $\leq$ 0V. Some of these curves are presented in figures 11 and 12 (negative values of capacitance were not to scale).

This is not the aim of this work to analyse the results of small-signal analyse performed by TOSCA. The aim is only to point out that usage of TOSCA based on "lifetime theory" gives results similar to that obtained with capacitance measurements.

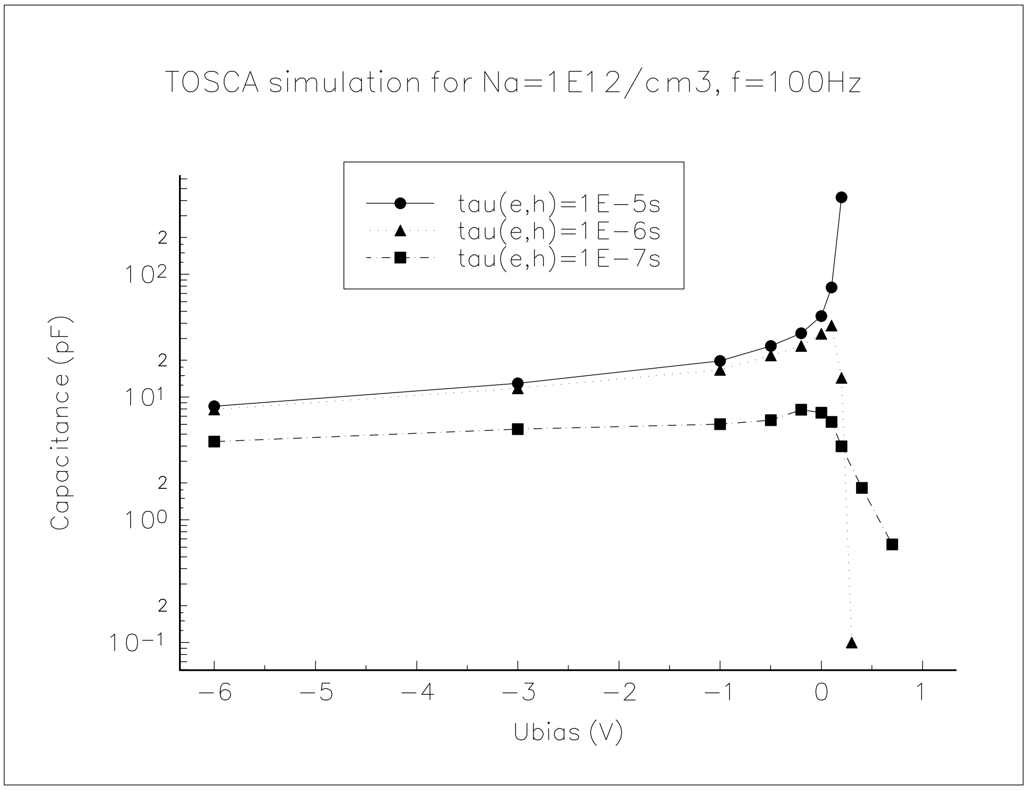


Figure 11: Diode model capacitance

5 Conclusions

It seems to be proved that the assumption on p - n junction existing beneath p+ contact in irradiated silicon diodes (detectors) is not necessary to explain a possibility of α-particle registration at low bias voltages and p+ side illumination.

It seems also to be proved that relaxation-material theory is not necessary to explain low-voltage maximum on C(Ubias) curve and negative values of capacitance of forward biased, heavily irradiated silicon diodes and detectors.

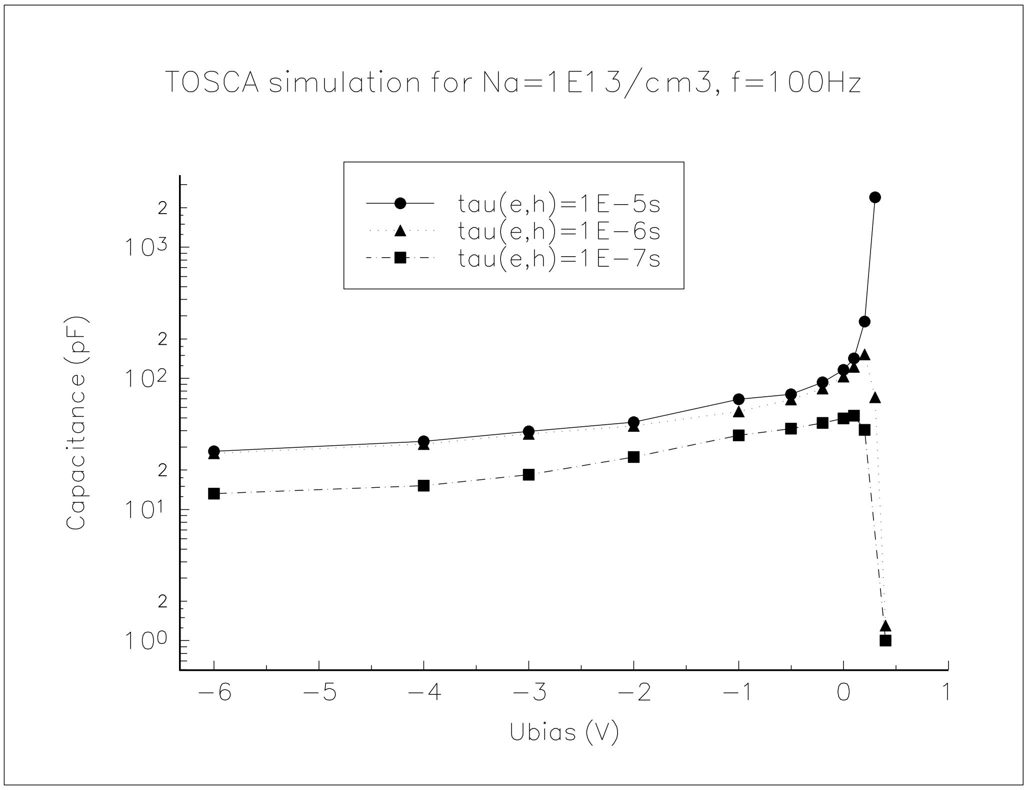


Figure 12: Diode model capacitance

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