TCAD Simulation of Complementary P- and N-type Silicon Low Gain Avalanche Detectors

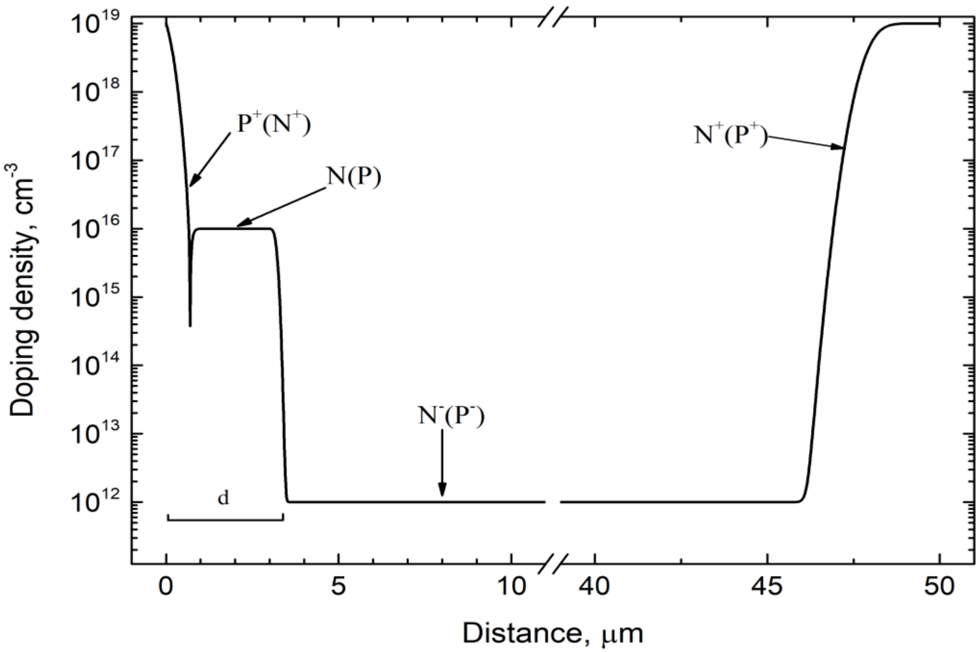
J.Vyšniauskas, L.Dundulis, K.Pūkas, E.Gaubas

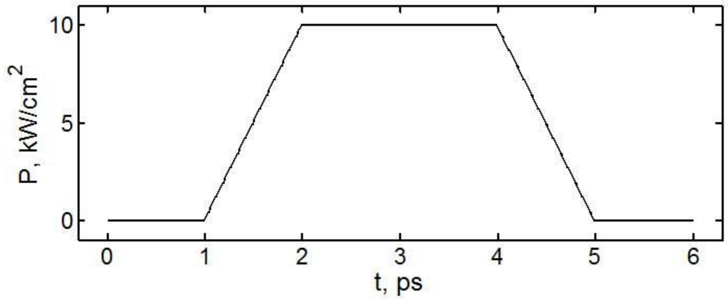
Vilnius University

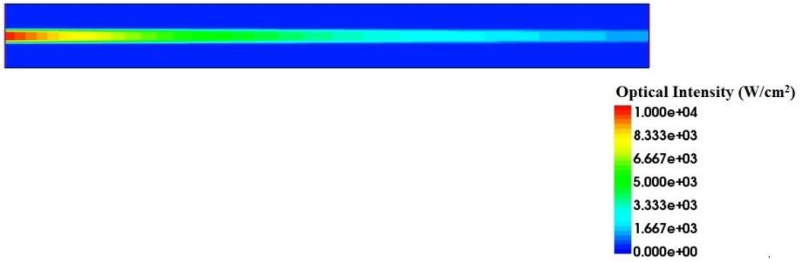
Introduction

Due to internal charge multiplication, Low Gain Avalanche Detectors (LGAD) enable to produce rather thin (~ 50 μm) silicon sensors with a relatively low operating voltage. A typical P-type LGAD consists of $N^+PP^-P^+$ layers with P-well formed by deep diffusion of boron into P^- layer. Another way of P-well formation by using an epitaxial process may lead to lower sensitivity of the breakdown voltage on N^+ layer thickness (**M.Carulla at al., 29th RD50 Workshop**). Possible boron compensation by radiation defects would cause gain degradation in P-type LGAD structures. This effect may be reduced by using N-type ($P^+NN^-N^+$) structure with a phosphorus doped N-well epitaxial layer. In this investigation we compared complementary P-type and N-type LGAD sensors.

Silicon LGAD Diode model with epitaxial N(P) layer





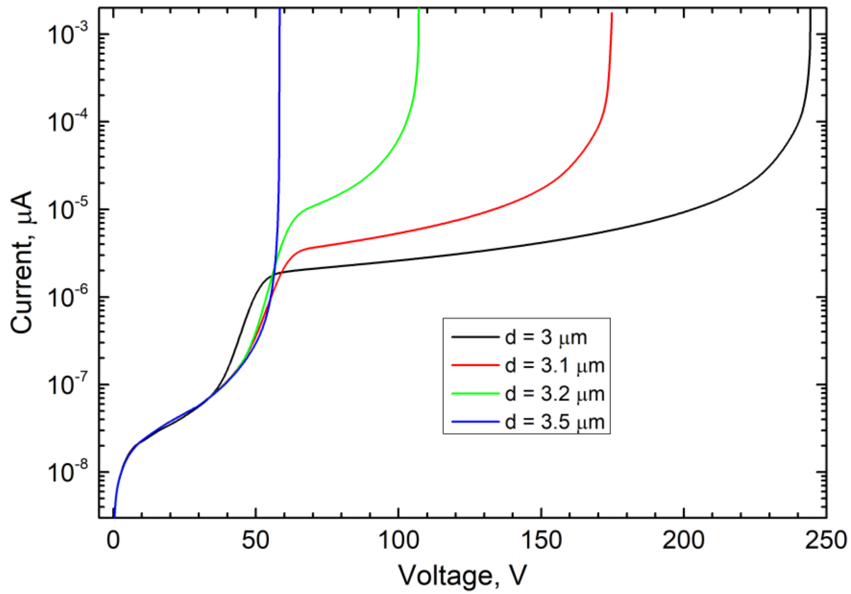


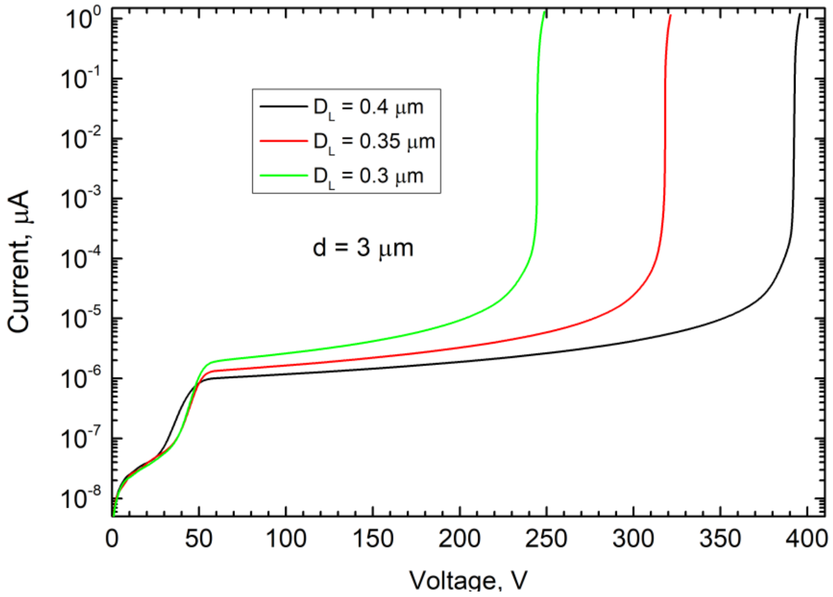
Drift-diffusion model according to Synopsys TCAD Sentaurus. Shockley–Read–Hall (SRH), Auger, recombination through two deep levels, and charge generation due to impact ionization (the van Overstraeten and de Man model) was taken into account.

Particle detection was emulated through photo-excitation of a 2×50 μm^2 excess carrier domain at the center of the active volume in a diode.

Constant voltage source connected to the diode.

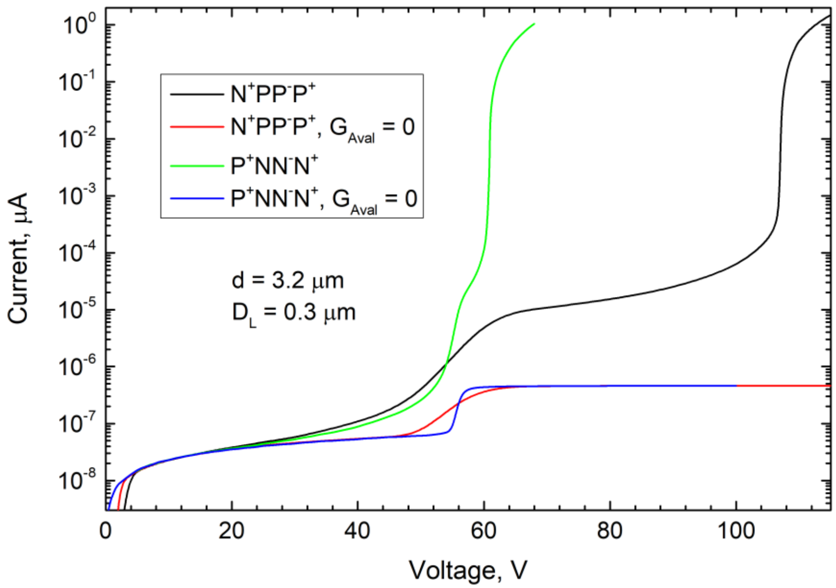
Results without traps (1)



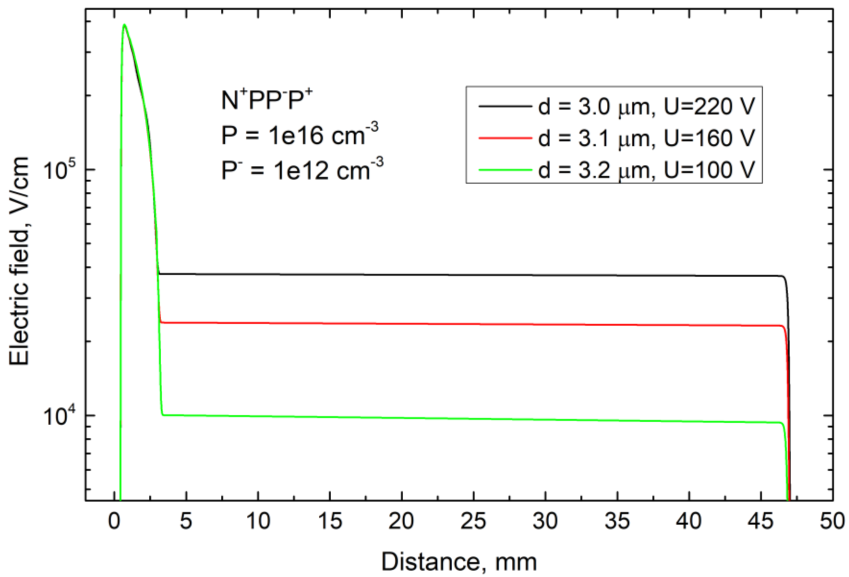


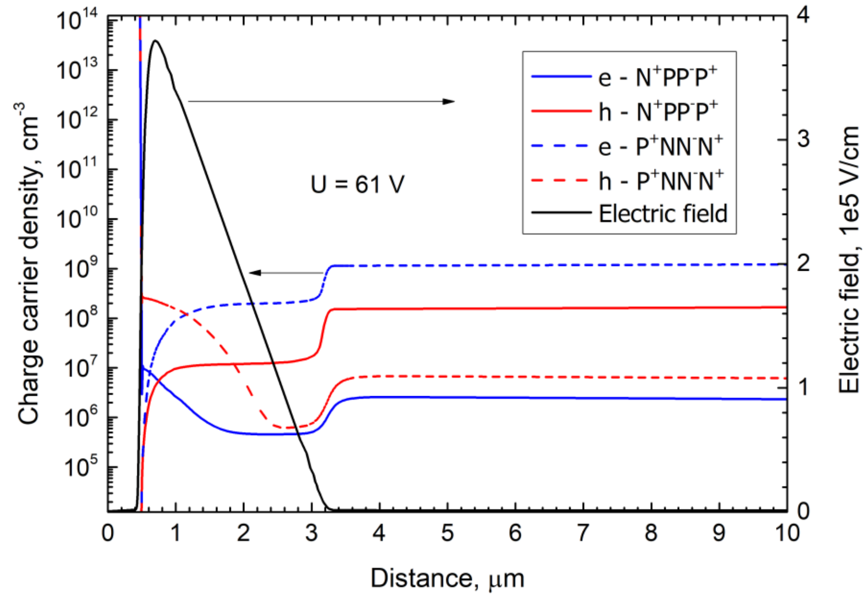
Our choice of diode structure

$N^+(P^+)$ = 1e19 cm^{-3}
P(N) = 1e16 cm^{-3}
$P^-(N^-)$ = 1e12 cm^{-3}
D_L = 0.3 µm
d = 3.2 µm

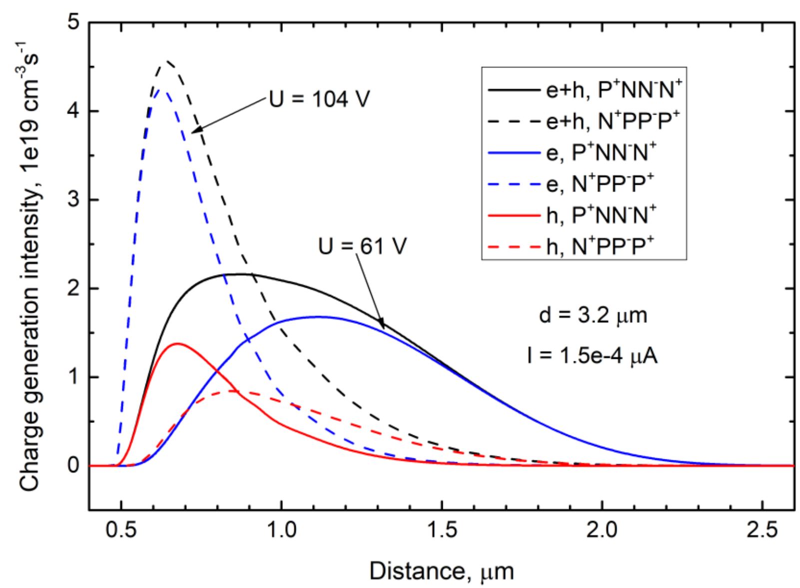


Results without traps (2)

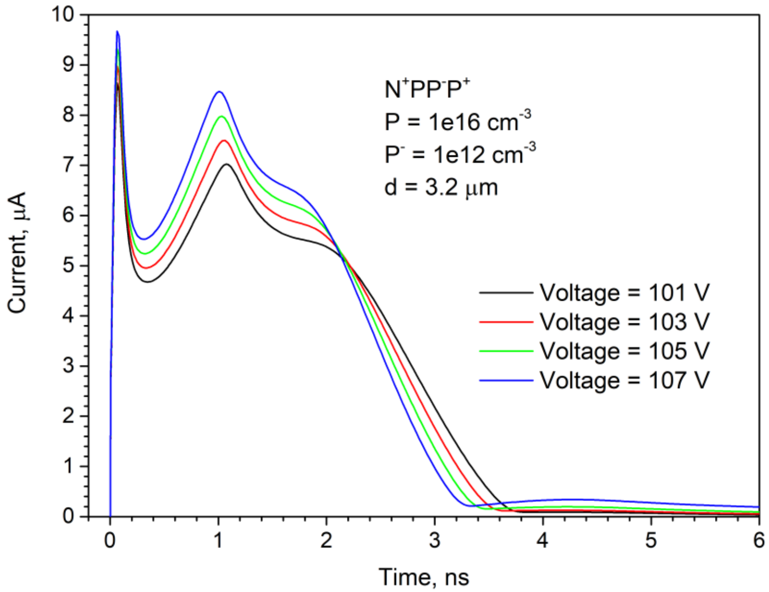


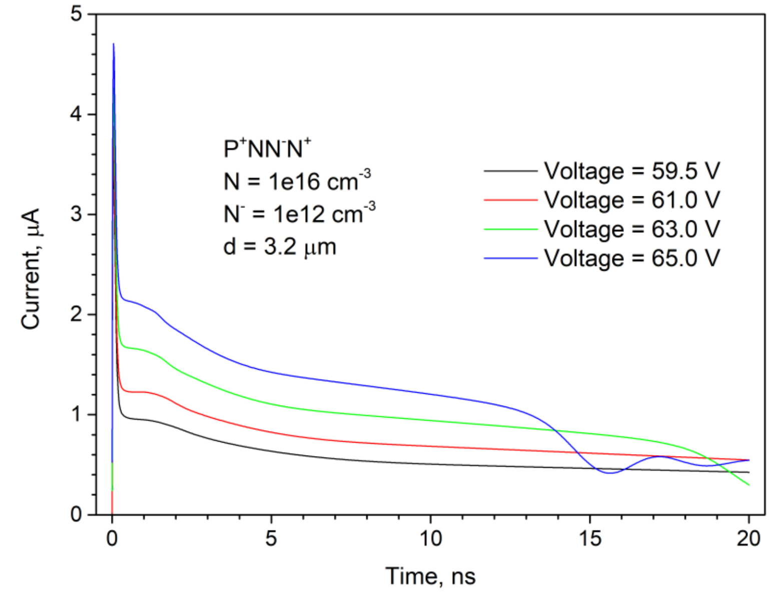


At U = 100 V, E = 10 kV/cm in P^- region, carriers move with saturation velocity v_s, extraction is quite fast.
At U = 61 V, E = 1.3 kV/cm in N^- region, carrier velocity is several times less, than v_s, extraction is very slow.

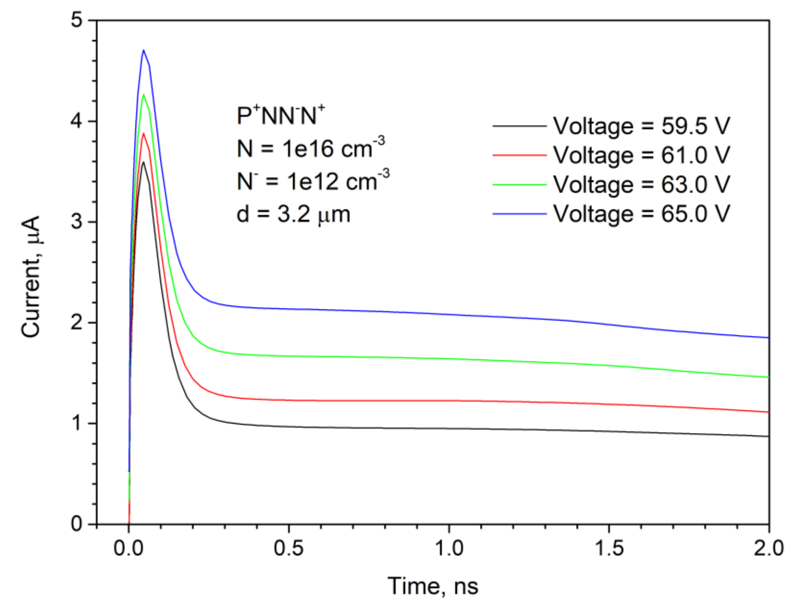


Results without traps (3)

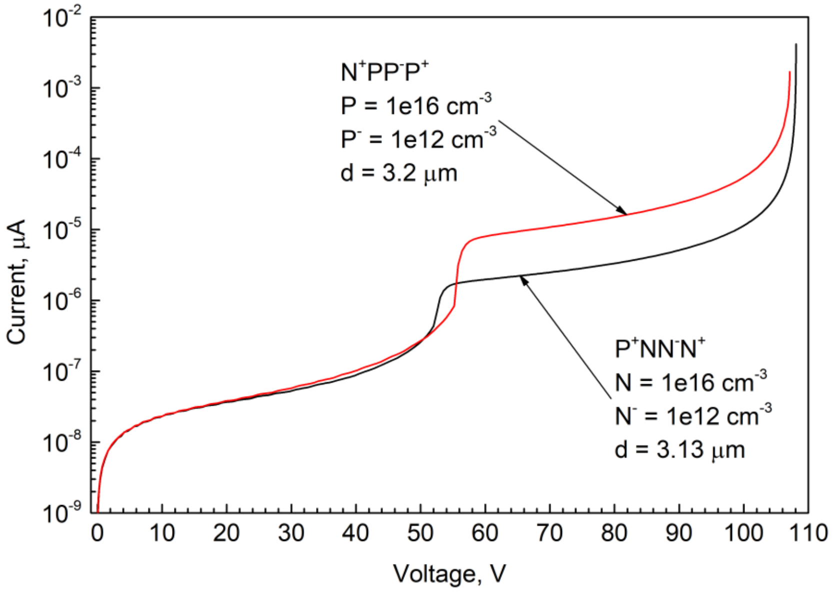


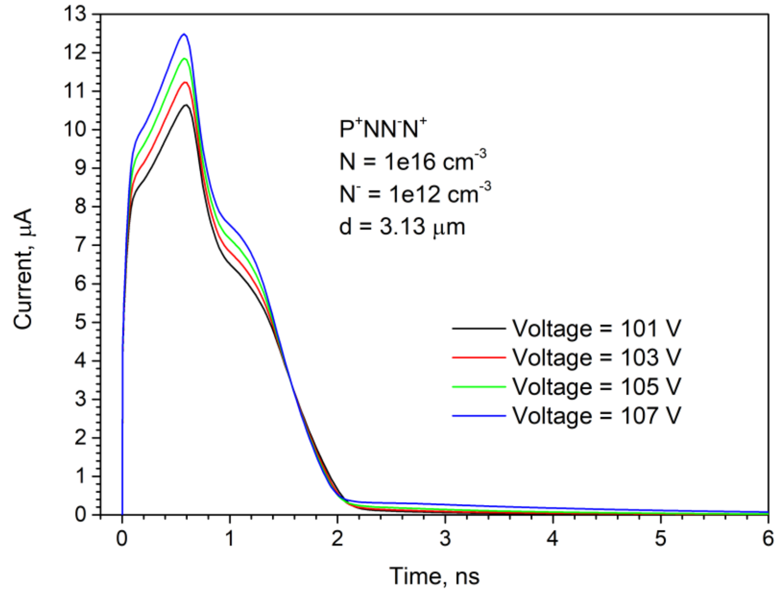


The current pulse shape and duration is quite different in P- and N-type diodes mainly due to the difference of the electric field in the region with low impurity density (N^{-},P^{-}) and due to the difference of the ionization coefficient of electrons and holes ($\alpha_e \cong 10\alpha_h$). But charge collection is almost the same in the absence of traps.

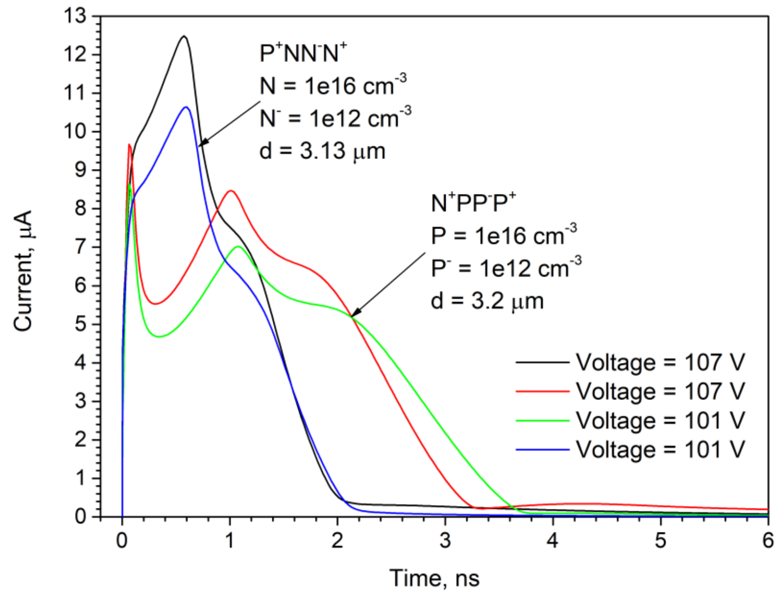


Results without traps (4)

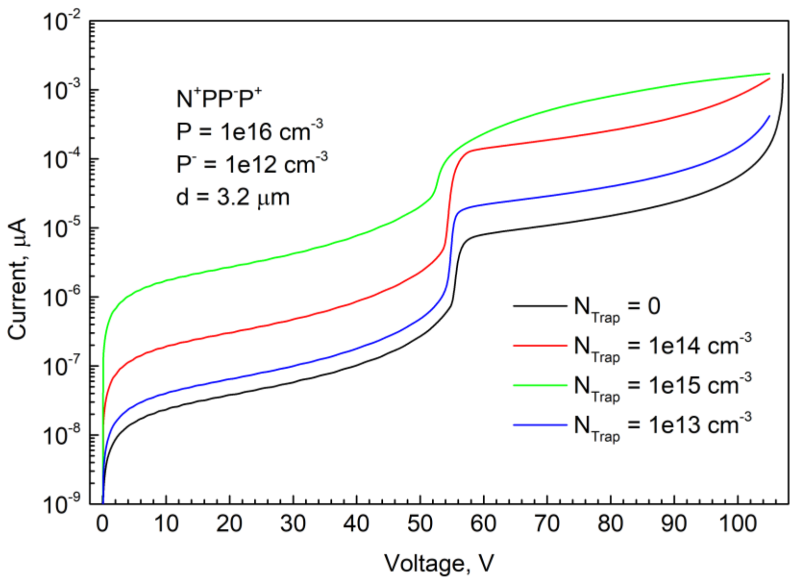


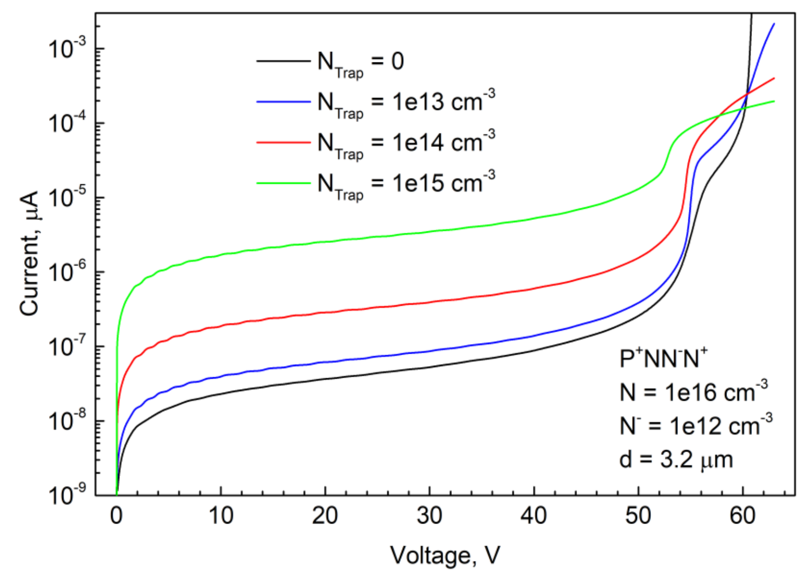


Decreasing of the epitaxial layer thickness by 70 nm in N-type diode (d = 3.13 nm) leads to similar (but not exactly the same) IV-characteristic as of the P-type diode with d = 3.2 μm.
CC = 1.40e-14 C, N-type, U = 105 V.
CC = 1.68e-14 C, P-type, U = 105 V.



Preliminary results with traps (1)

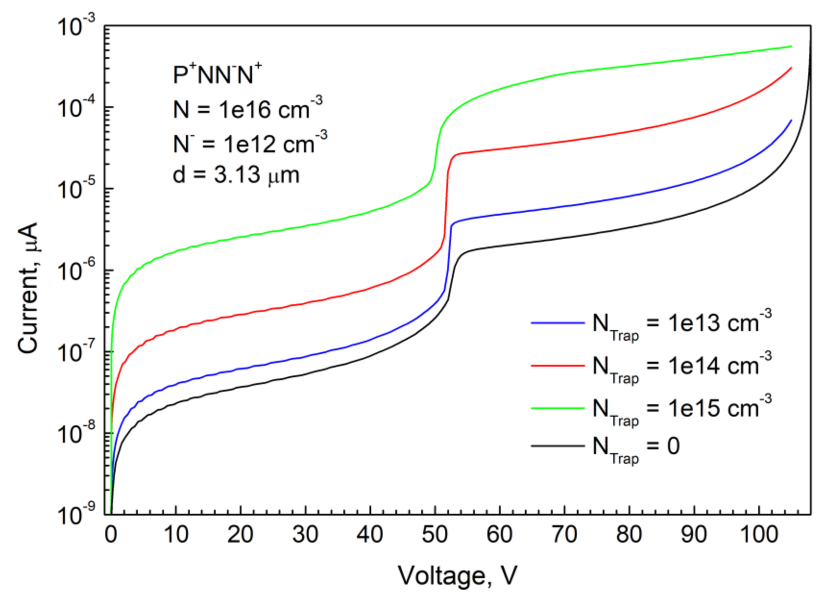




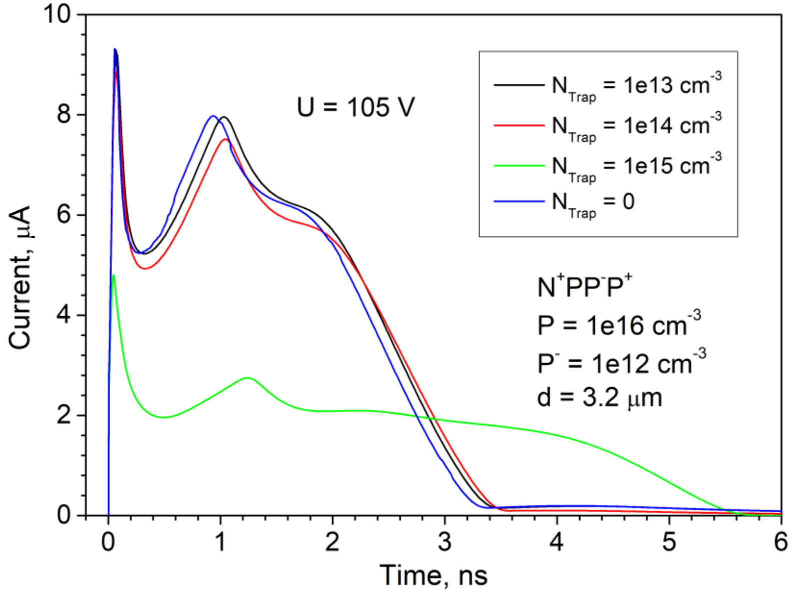
Traps: modified R.Dalal et al. [1] model

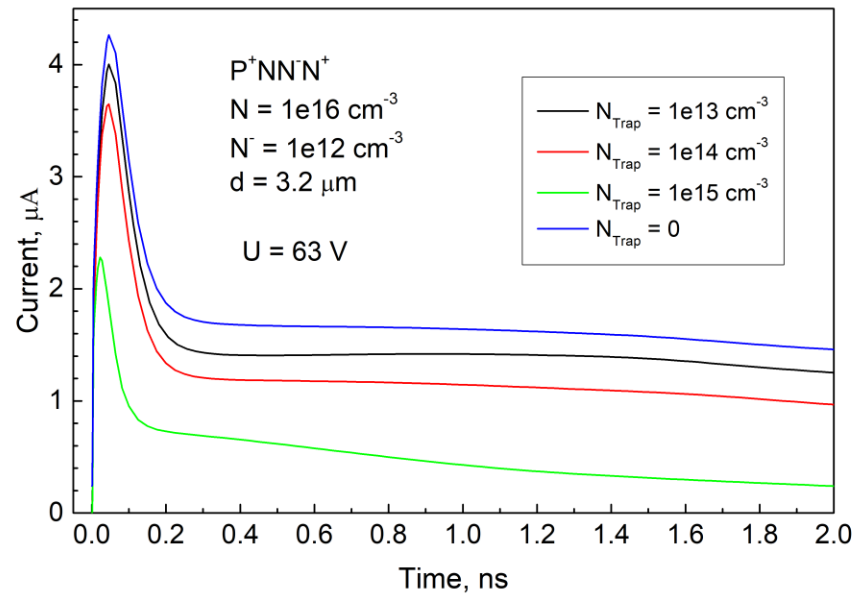
Acceptor E_c- 0.51 eV, N_{Trap} = 1e13, 1e14, 1e15 cm^{-3}
σ_e = 2e-14 cm^2, σ_h = 3.8e-15 cm^2
Donor E_v+ 0.48 eV, N_{Trap} = 1e13, 1e14, 1e15 cm^{-3}
σ_e = 2e-15 cm^2, σ_h = 2e-15 cm^2

[1] NIMPR A 836 (2016) 113–121



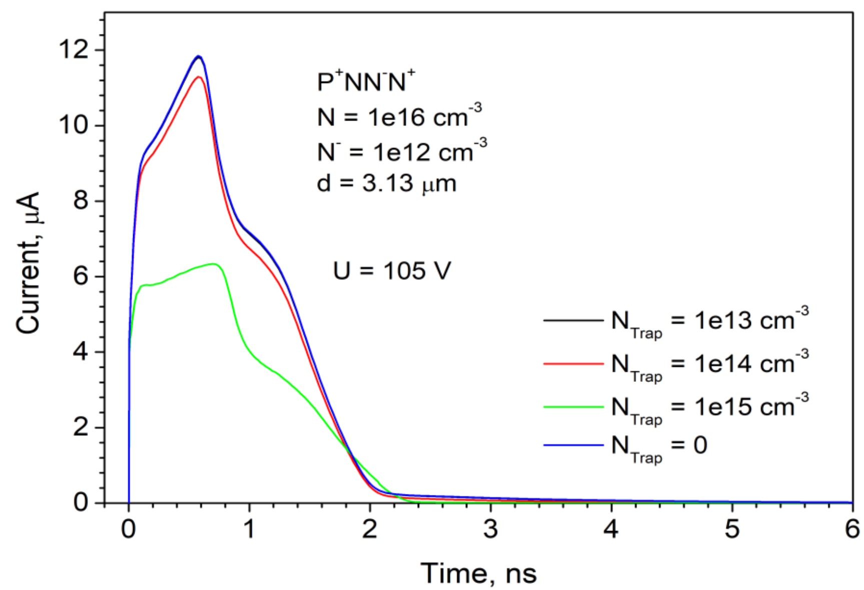
Preliminary results with traps (2)





Charge collection at N_{Trap} = 1e15 cm^{-3} Time interval = 20 ns

CC = 1.0e-14 C, P-type, d = 3.2 μm, U = 105 V
CC = 1.5e-15 C, N-type, d = 3.2 μm, U = 63 V
CC = 7.7e-15 C, N-type, d = 3.13 μm, U = 105 V



Conclusions

1. Operation of complementary P- and N-type LGAD diodes is different.

2. The breakdown voltage of P-type diode is almost two times higher than of the N-type diode with the same epitaxial layer thickness. The main reason: electron density in the multiplication region is higher in N-type diodes and ionization coefficient of electrons is much higher than corresponding coefficient of holes.

3. Due to low breakdown voltage of N-type diode the electric field in the N^{-} layer is quite low (1.3 kV/cm), carriers move with the velocity several times lower than the saturation velocity. Carrier extraction is slow (50-60 ns) in comparison with P-type diode (3-4 ns).

4. The charge collection in P- and N-type diodes is the same in the case of no traps.

5. The equal breakdown voltage of P- and N-type diodes can be achieved by adjusting the epitaxial layer thickness (d = 3.2 μm in P-type diode and d = 3.13 μm in N-type diode).

6. In the presents of traps (N_{Trap} = 1e15 cm^{-3}) charge collection in P-type diode is 6.7 time higher than in the corresponding N-type diode with the same epitaxial layer thickness d = 3.2 μm. In the case of equal breakdown voltage the charge collection in P-type diode exceeds the charge collection in N-type diode by 30 percent.

Thank you!