27th RD-50 Workshop

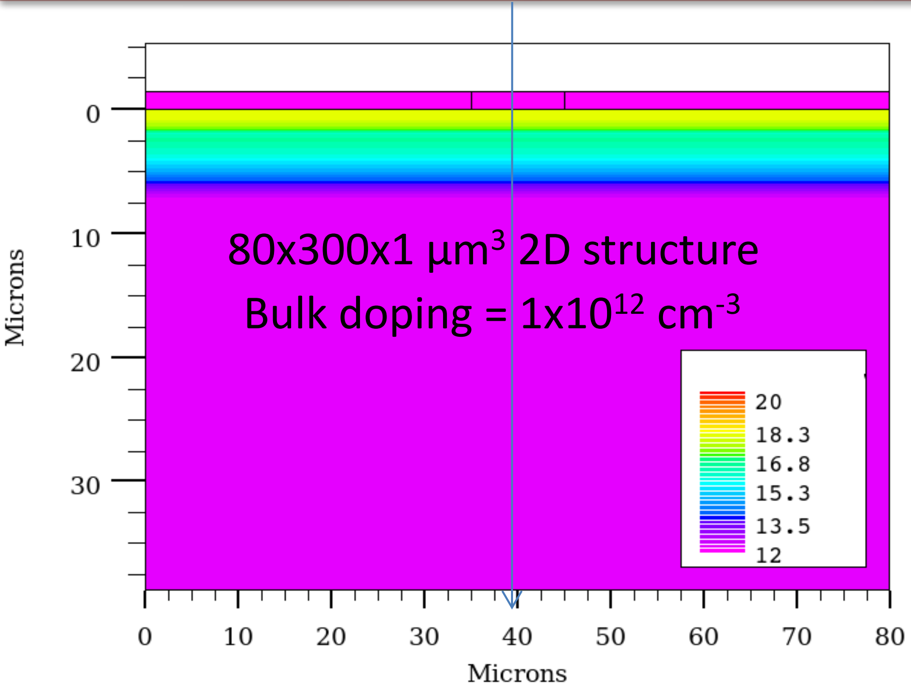
TCAD simulation for Low Gain Avalanche Detectors

Ranjeet Dalal*, Ashutosh Bhardwaj, Kirti Ranjan, Geetika Jain

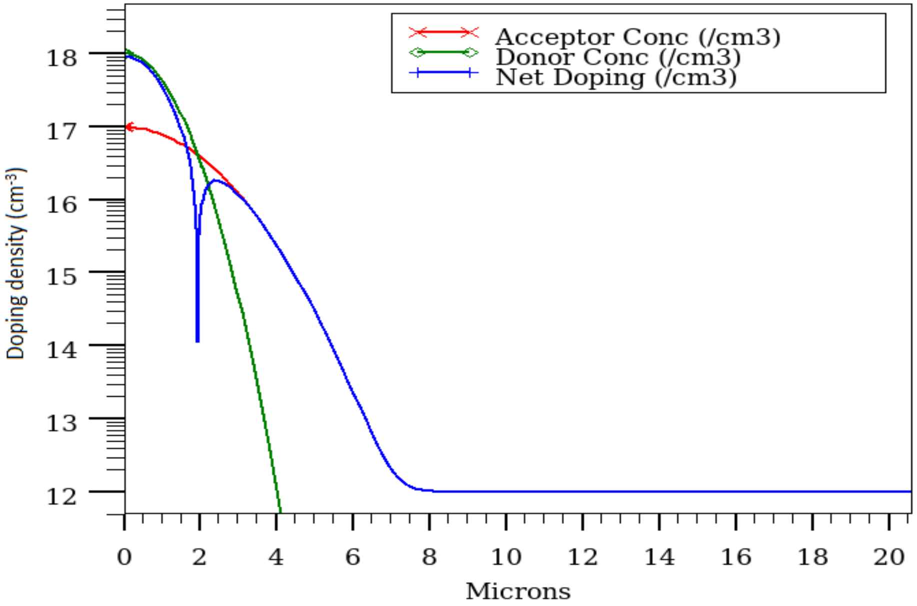
Work done under RD-50 collaboration

*rdalal@cern.ch

Simulation structure



Simulation Structure (Zoomed view)



Doping profile for a typical p-well region

- Silvaco TCAD tool is used for simulation

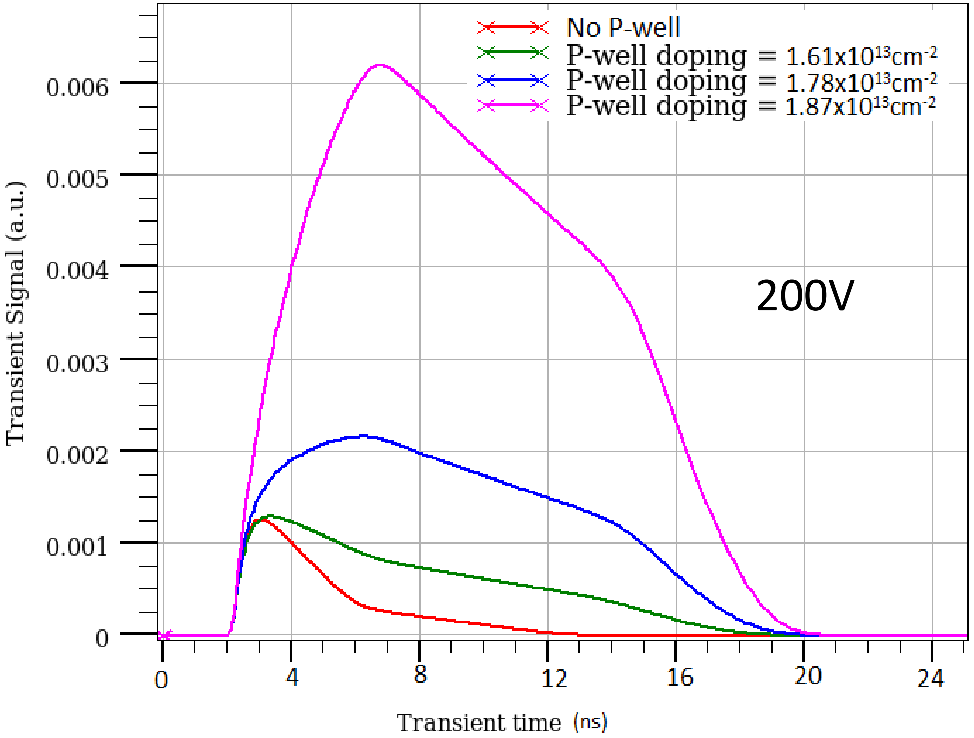
-Initially, p-well depth (d_p) of 7 µm is kept (taken clues from earlier publications), p-well dose (N_p) varied (by varying peak doping density)

- n^+ doping depth (d_n) of 4 µm with peak doping density (N_n) equal to 1×10^{18} cm^{-3} is used.

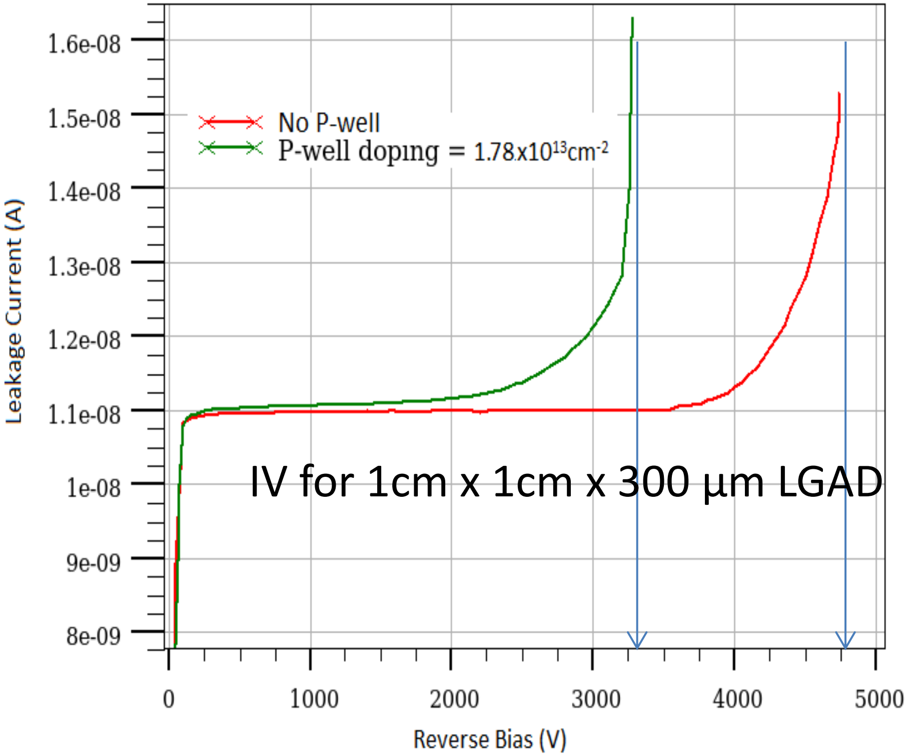
-Gaussian Doping profiles are used.

  - Infrared laser from top (1060 nm, 1µm wide)
  - External circuit elements, similar to DU TCT setup, are implemented

Methodology



200V



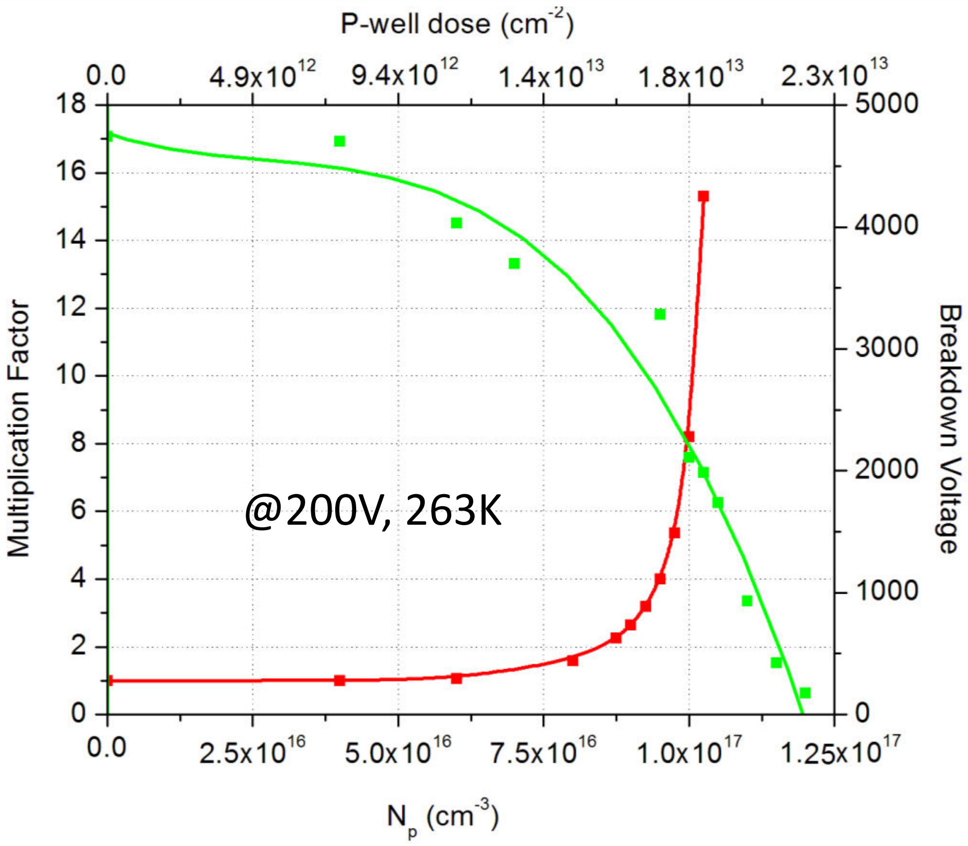
IV for 1cm x 1cm x 300 µm LGAD

- Multiplication factor (MF) or Gain is defined w.r.t. simple diode of same dimension.

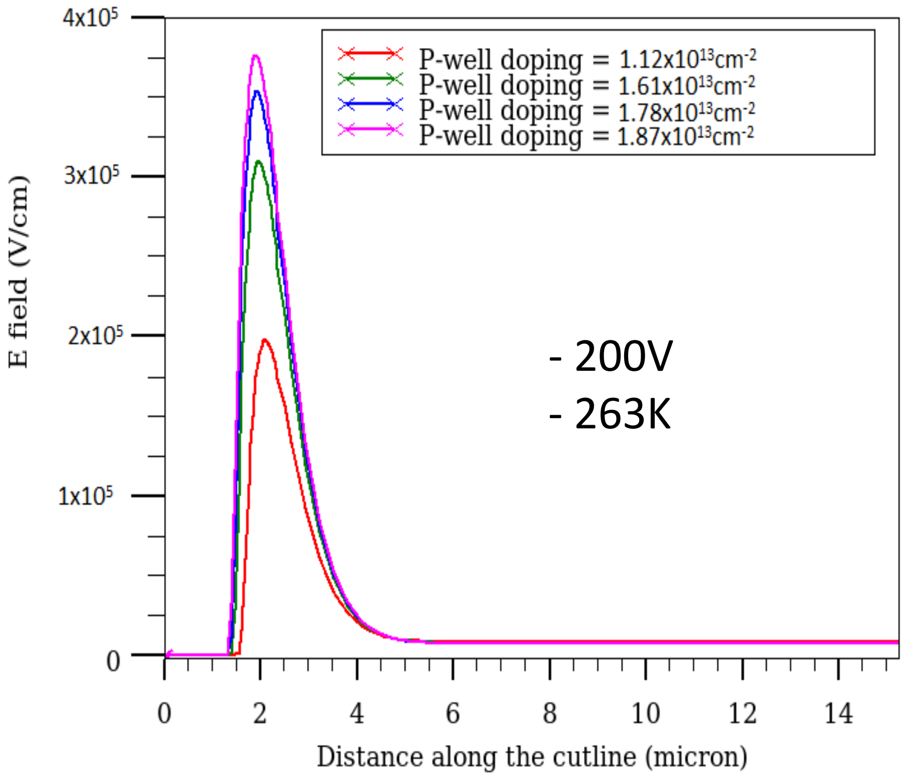
  MF = (Inte. Charge for given design)/ (Inte. Charge for Diode)

- Breakdown voltage is extracted from IV plots
  - Separate structures with/without any edge termination structures are used
  - Shown in backup slides

P-well dose variation effect



@200V, 263K



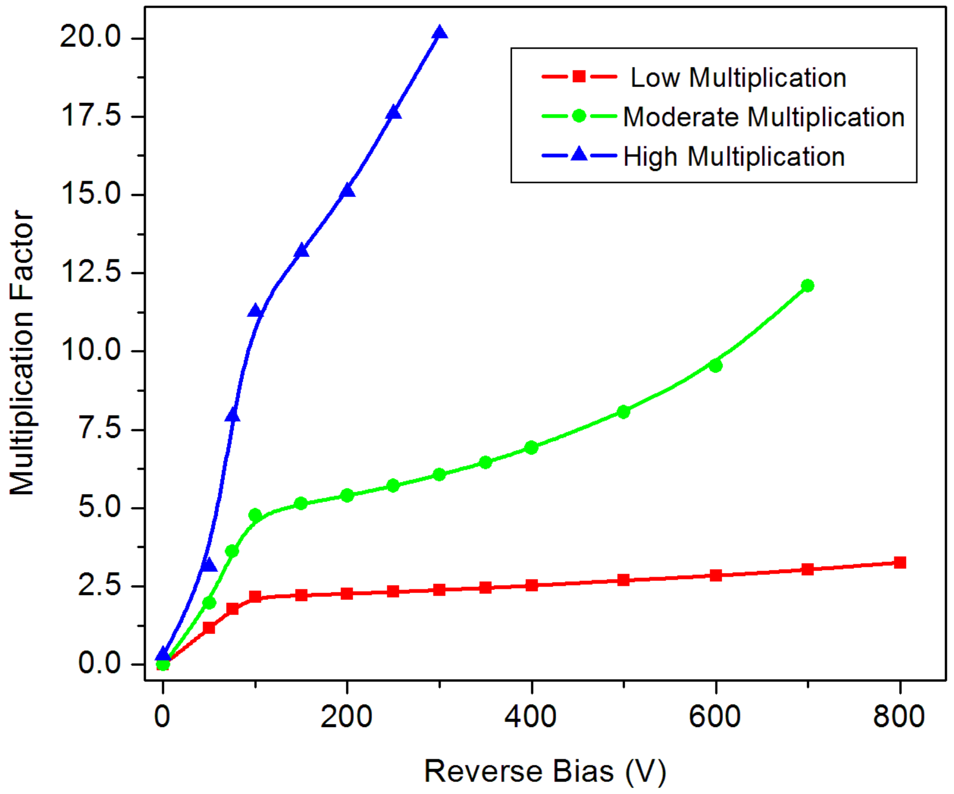
- 200V
- 263K

- Multiplication factor (MF) increases with p-well dose (or peak doping density) for a given depth (7 µm in present plot).
- Breakdown voltage deceases with higher p-well dose (or peak doping)
- The p-well doses (extracted from simulation approach) are similar to experimentally reported values[1]

Peak doping density 8.75e16cm^{-3} equal to dose 1.61e13 cm^{-2}
peak doping density 9.75e16cm^{-3} equal to dose 1.78e13 cm^{-2}
Peak doping density 1.025e17cm^{-3} equal to dose 1.87e13 cm^{-2}

[1] G. Pellegrini, Hiroshima 2014, NIMA

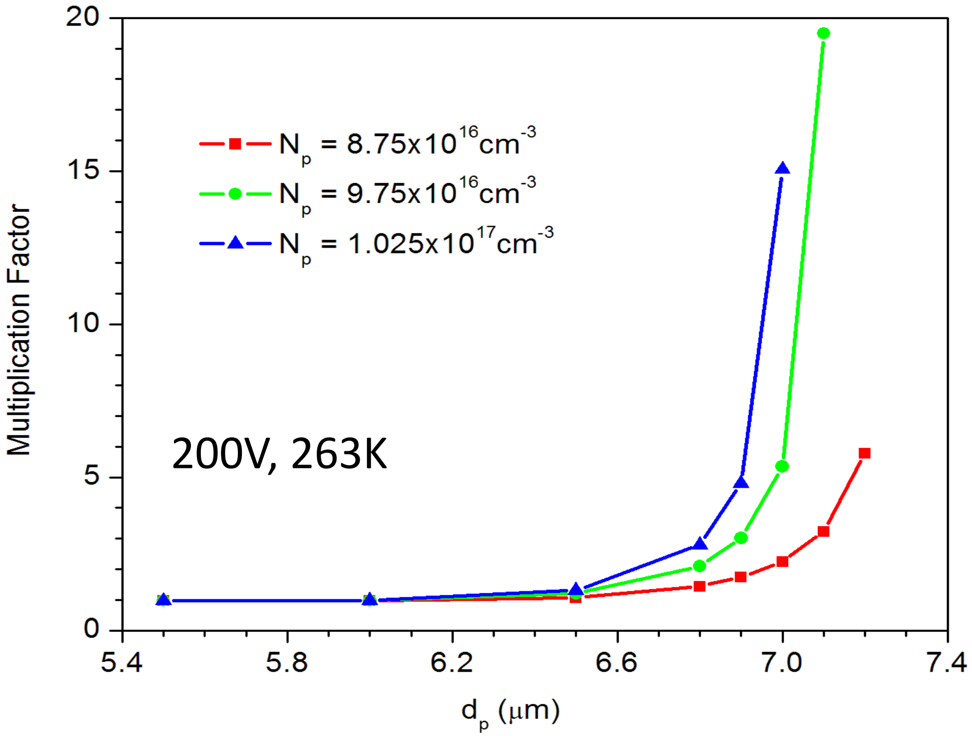
Three different multiplication cases

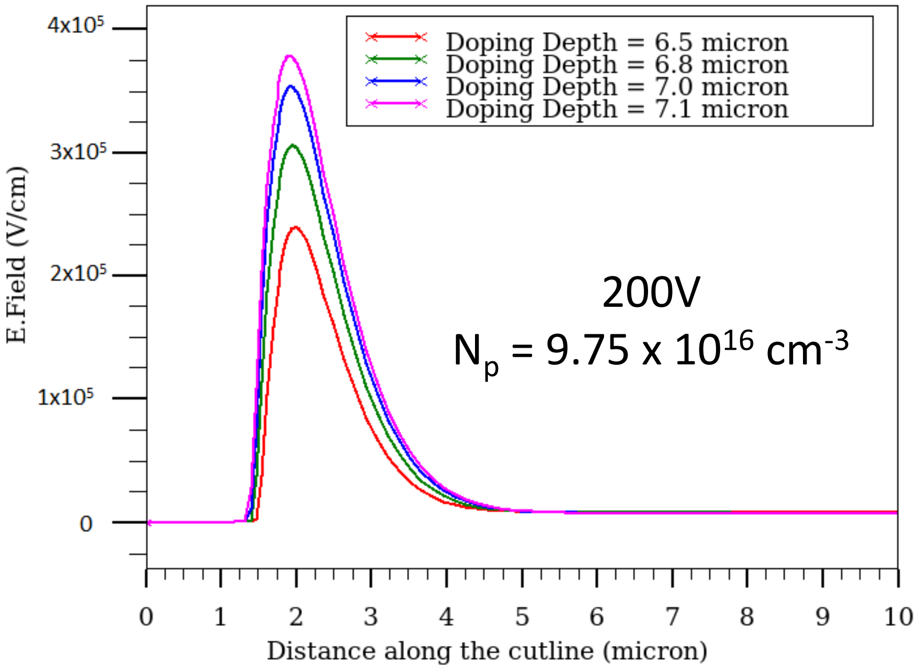


Three different multiplication cases selected for detailed investigation

- Low multiplication with p-well peak doping density (N_p) equal to 8.75×10^{16}cm^{-3} (or dose 1.61×10^{13} cm^{-2})
  - Multiplication factor about 2.5 at 200V
- Moderate multiplication with N_p equal to 9.75×10^{16}cm^{-3} (or dose 1.78×10^{13} cm^{-2})
  - Multiplication factor about 5 at 200V
- High multiplication with N_p equal to 1.025×10^{17}cm^{-3} (or dose 1.87×10^{13} cm^{-2})
  - Multiplication factor of about 15 at 200V

P-well concentration and depth variation





n^+ peak doping density = $1 \times 10^{18} cm^{-3}$, 4µm

MF increases with increasing p-well doping depth (for a given p-well peak doping density)

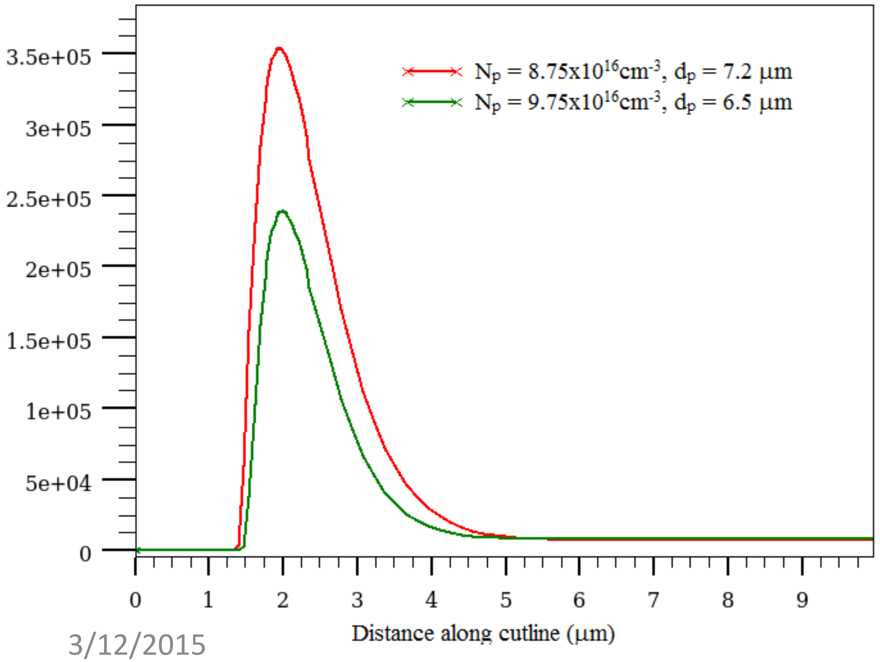
-Increasing p-well doping depth (for a give peak doping density)

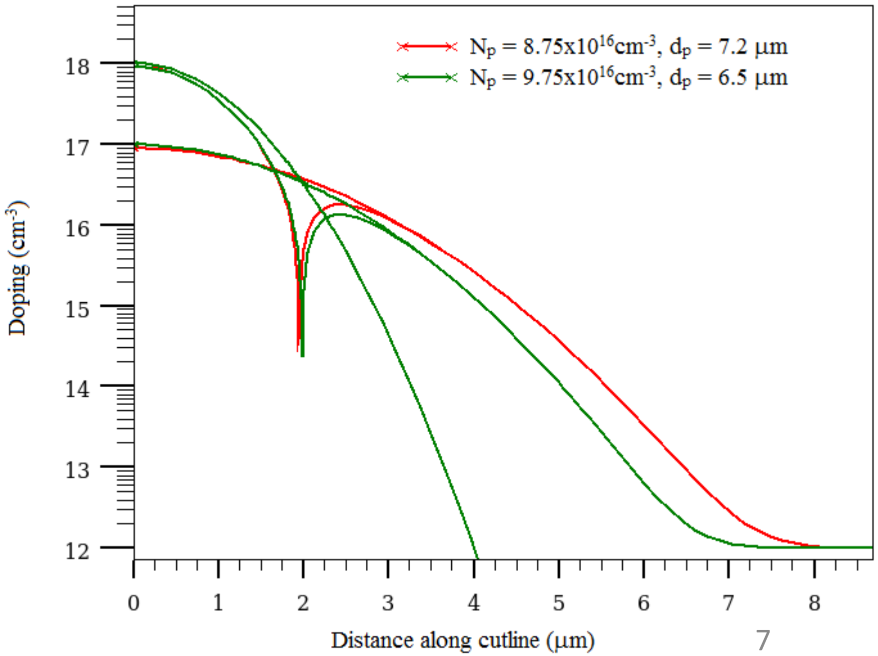
- Results in higher acceptor concentration around n^+/p-well junction
- It results in higher field and higher MF

Dose (& MF) Matrix for p-well

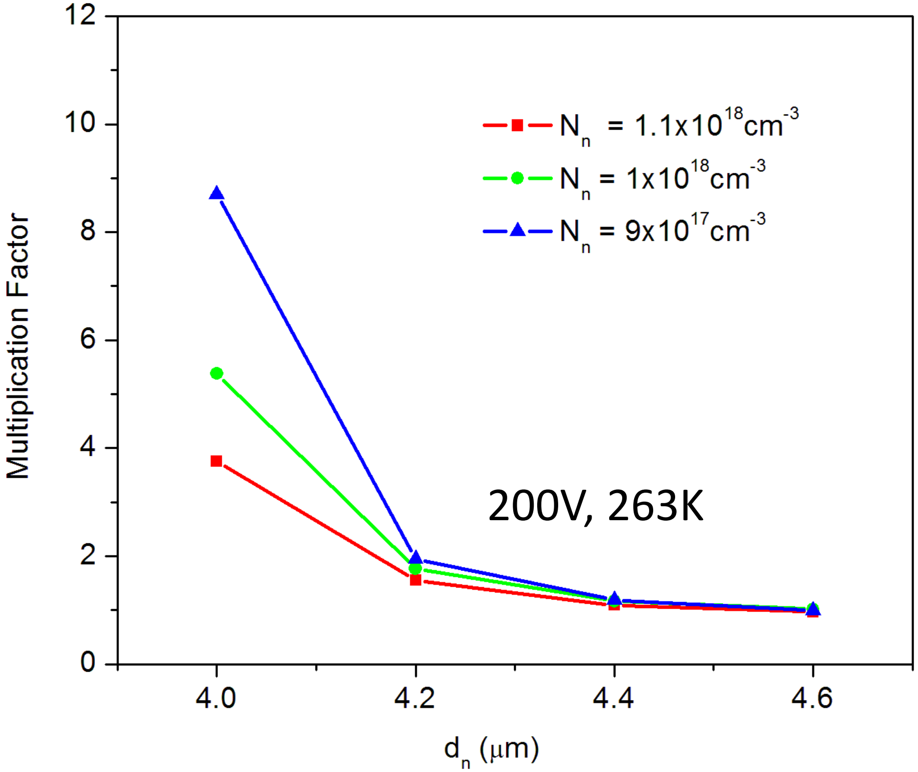
Total p-well dose (& MF @ 200V) table for different p-well doping depth and peak values (n^+ profile kept constant, n^+ doping density = 1×10^{18} cm^{-3}, depth = 4µm)

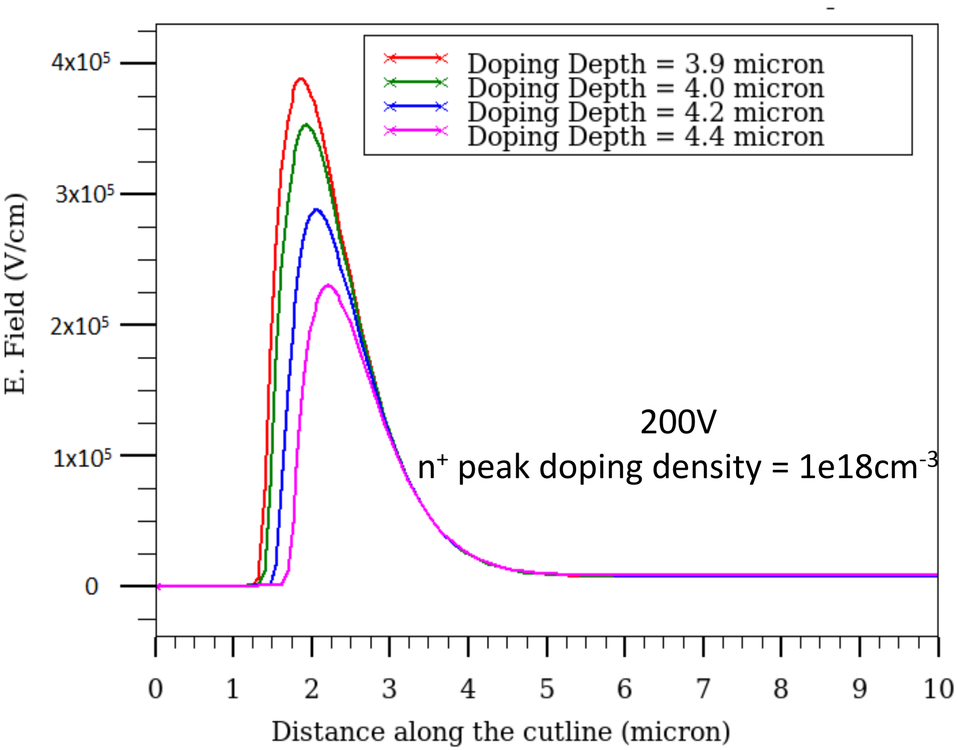
Peak p-well doping (cm^{-3})	p-well depth=5.5µm	6 µm	6.5 µm	6.8 µm	6.9 µm	7 µm	7.1 µm	7.2 µm
8.75×10^{16}	1.264e13 (0.97)	1.379e13 (0.97)	1.493e13 (1.07)	1.563e13 (1.44)	1.586e13 (1.74)	1.609e13 (2.25)	1.632e13 (3.23)	1.655e13 (5.78)
9.75×10^{16}	1.402e13 (0.97)	1.529e13 (.98)	1.657e13 (1.20)	1.733e13 (2.10)	1.759e13 (3.02)	1.784e13 (5.35)	1.810e13 (19.49)	1.836e13
1.025×10^{17}	1.470e13 (0.97)	1.604e13 (0.98)	1.738e13 (1.31)	1.818e13 (2.80)	1.845e13 (4.80)	1.872e13 (15.06)	1.899e13	1.925e13





n^+ concentration and depth variation





p-well peak doping density = 9.75 x10^{16}cm^{-3}, depth = 7 μm

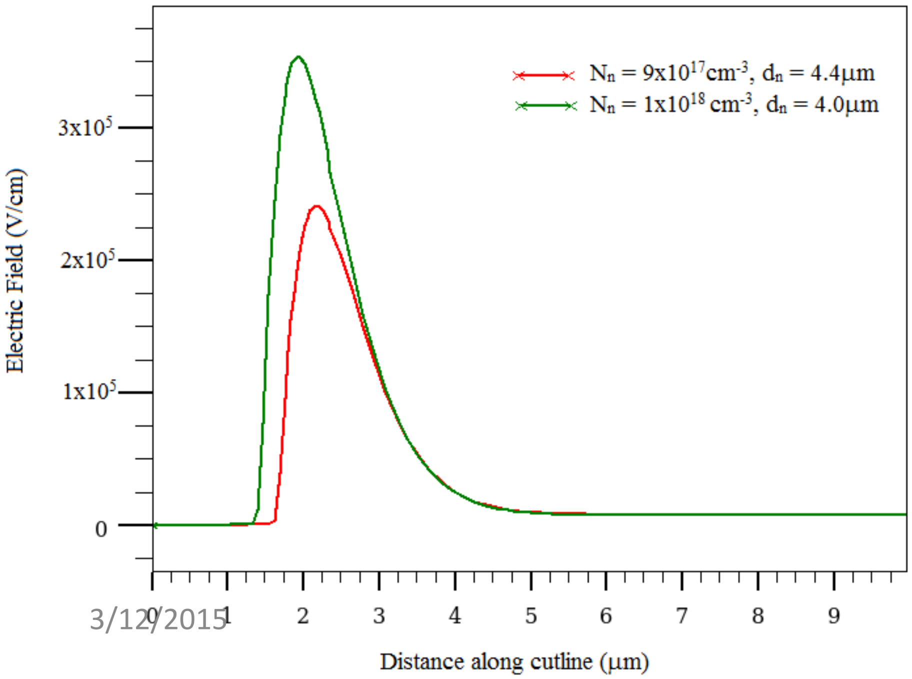
Multiplication factor is strongly affected by n^+ doping profile too.

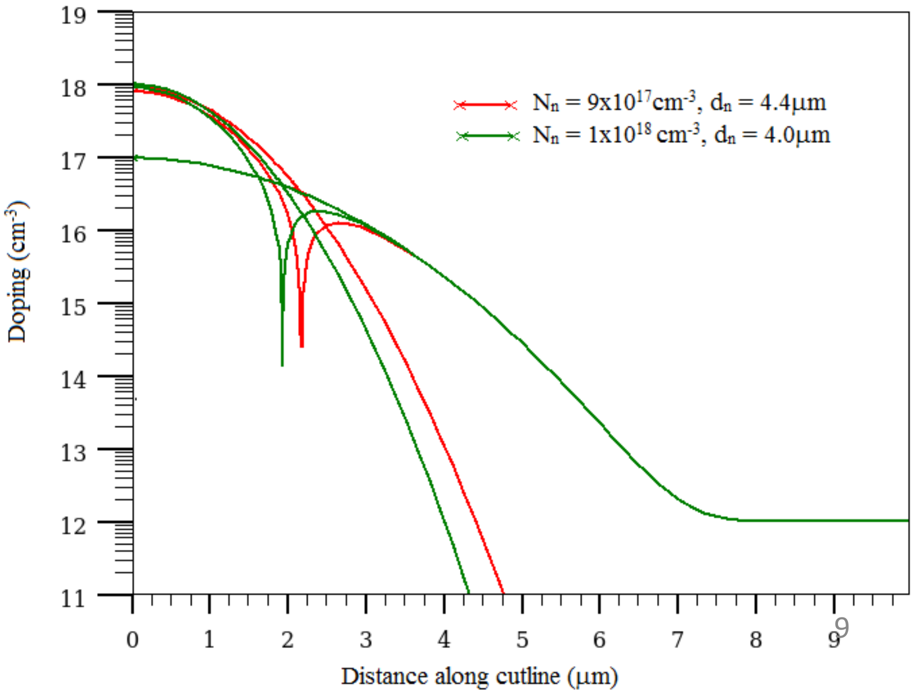
- Lower n^+ doping depth (for a given n^+ peak doping density) ---- Higher MF
- Lower n^+ peak doping density (for a given n^+ depth) ---- Higher MF

Dose (& MF) Matrix for n^+ doping profile

Total n^+ dose (& MF @ 200V) table for different n^+ doping depth and peak values
(p-well doping profile kept constant, p-well doping density = 9.75×10^{16} cm^{-3}, depth = 7µm)

Peak n^+ doping (cm^{-3})	n^+ depth=3.9µm	4 µm	4.2 µm	4.4 µm	4.6 µm
9 x10^{17}	8.392e13	8.609e13 (8.70)	9.040e13 (1.95)	9.471e13 (1.19)	9.902e13 (1)
1 x 10^{18}	9.290e13 (169.55)	9.529e13 (5.35)	1.001e14 (1.77)	1.048e14 (1.17)	1.096e14 (1)
1.1 x 10^{18}	1.018e14 (14.28)	1.045e14 (3.76)	1.097e14 (1.55)	1.149e14 (1.09)	1.201e14 (0.97)





Irradiation effect

Radiation damage simulations are carried out using already published and tested two trap model (R. Dalal et al., Vertex-2014)

- It was developed during HPK campaign for proton irradiation
- It creates correct amount of leakage current, full depletion voltage (or CV), double peak electric field profile and CCE for fluence at least up to 2e15 $n_{eq}cm^{-2}$

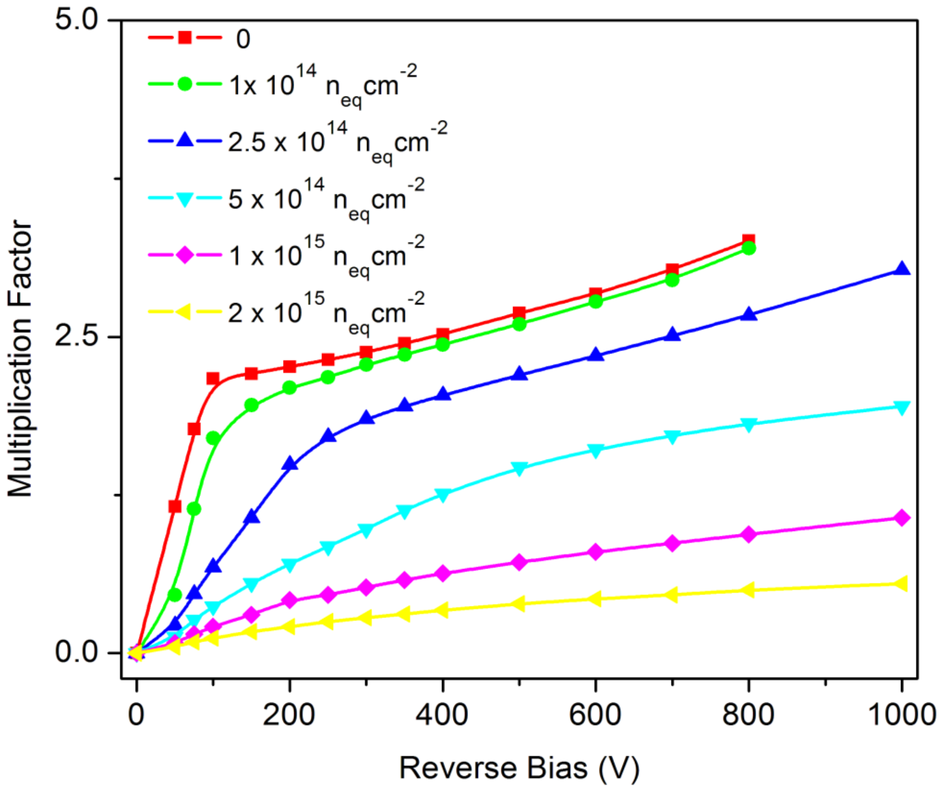
No acceptor removal term have been used in these simulations

- Simulations are carried out at 253K

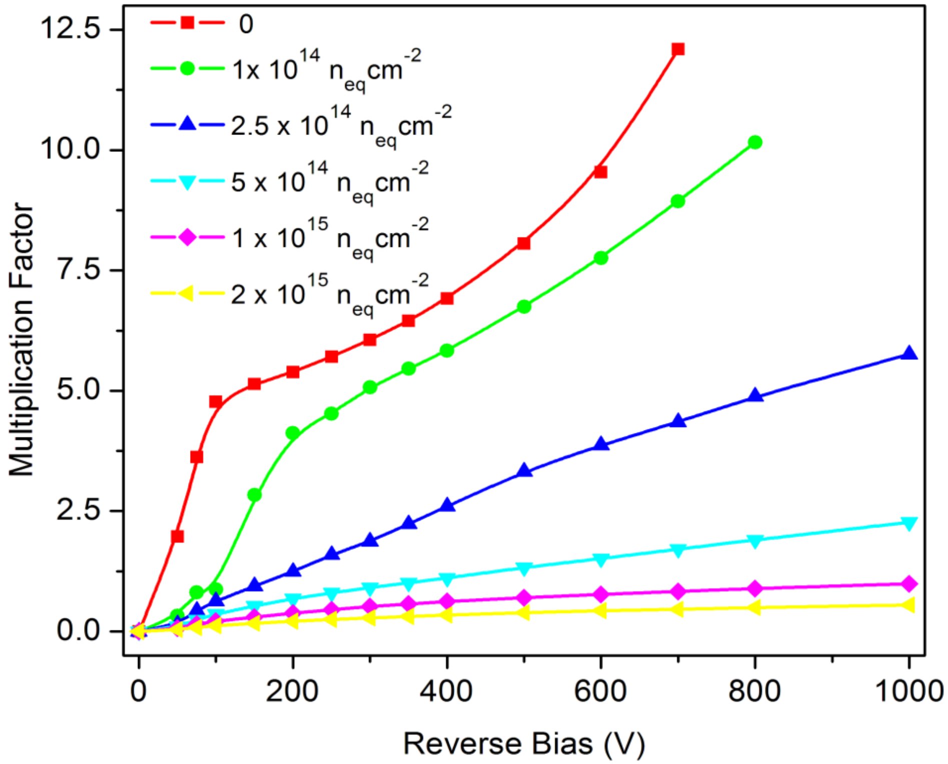
No.	Trap	Energy Level	g_{int} (cm^{-1})	σ_e (cm^{-2})	σ_h(cm^{-2})
1.	Acceptor	E_c-0.51eV	4	$2\text{x}10^{-14}$	$3.8\text{x}10^{-15}$
2.	Donor	E_v+0.48eV	3	$2\text{x}10^{-15}$	$2\text{x}10^{-15}$

Parameter table for two trap model used in present simulations

Irradiation effect on multiplication factor-1



Low multiplication LGAD design

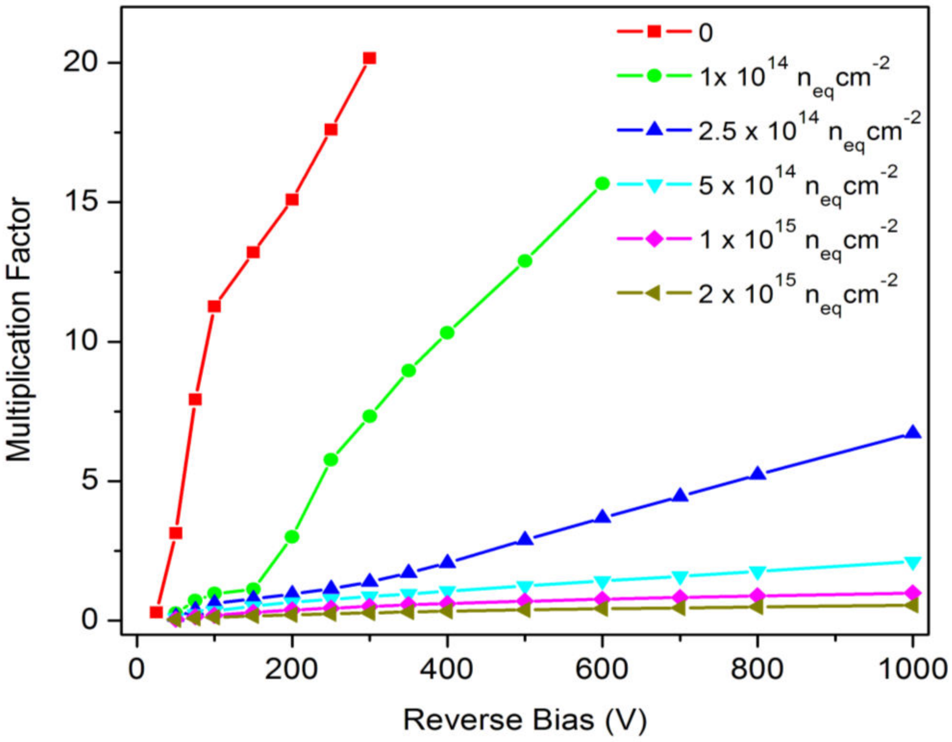


Moderate multiplication LGAD design

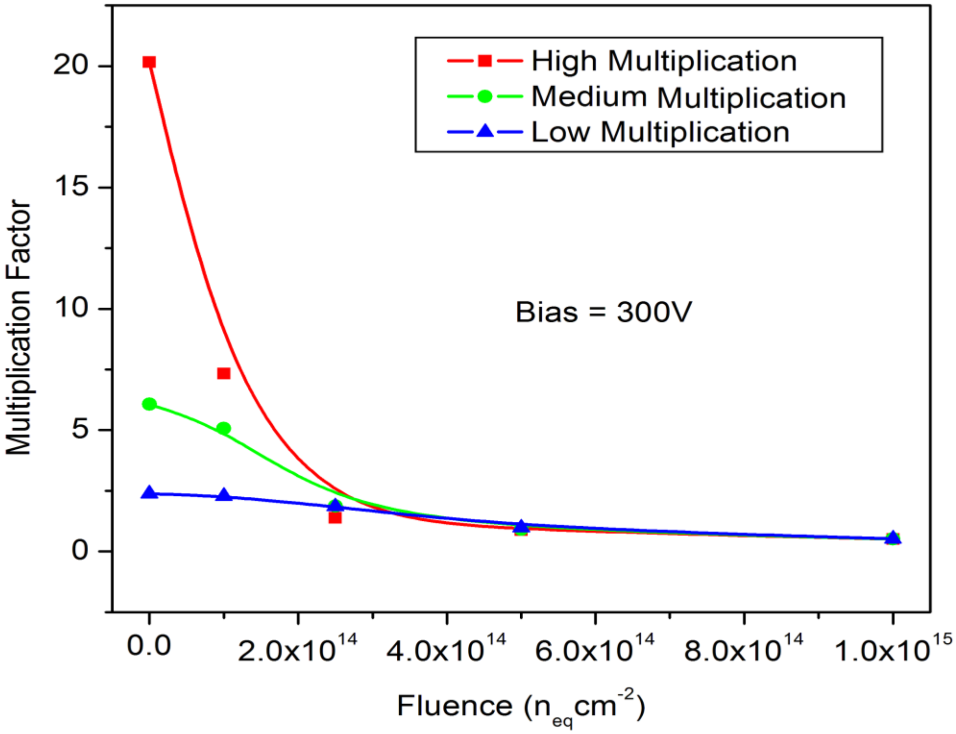
Charge multiplication factor is strongly affected by irradiation

- Very little or no multiplication for fluence $1\times10^{15}\ n_{eq}cm^{-2}$ and above

Irradiation effect on multiplication factor-2



High Multiplication LGAD design

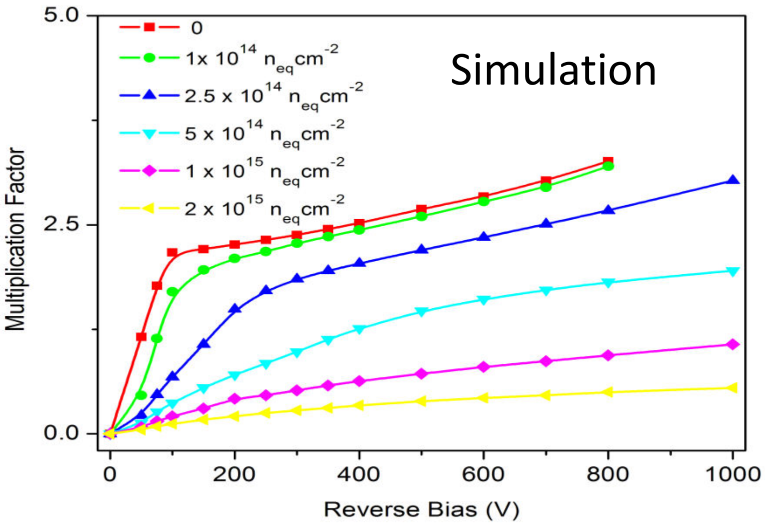


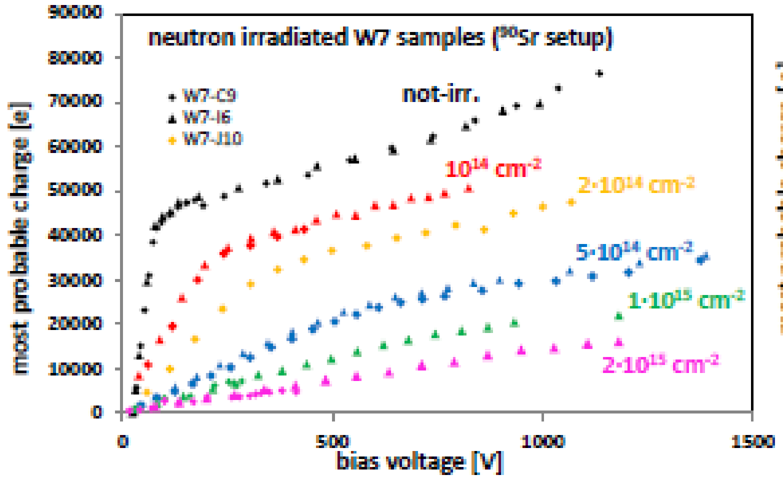
Multiplication variation with fluence

Sharper decrease of MF for high multiplication case

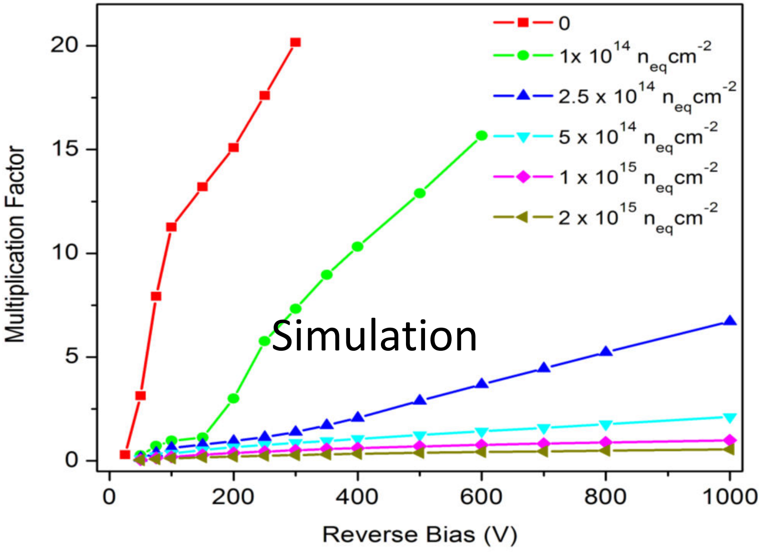
- MF is practically same for all the fluence ≥ 2.5 x 10^{14} $n_{eq}cm^{-2}$
- Almost no multiplication for fluence ≥ 5 x 10^{14} $n_{eq}cm^{-2}$

Some published measurements





Kramberger, JINST 2015



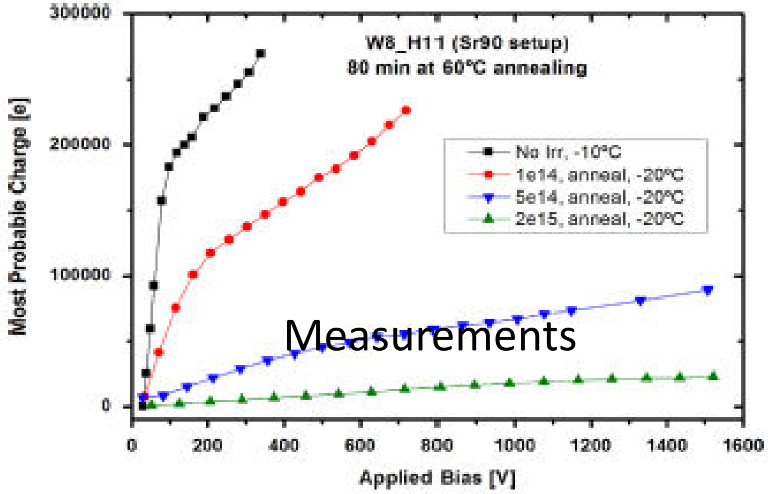


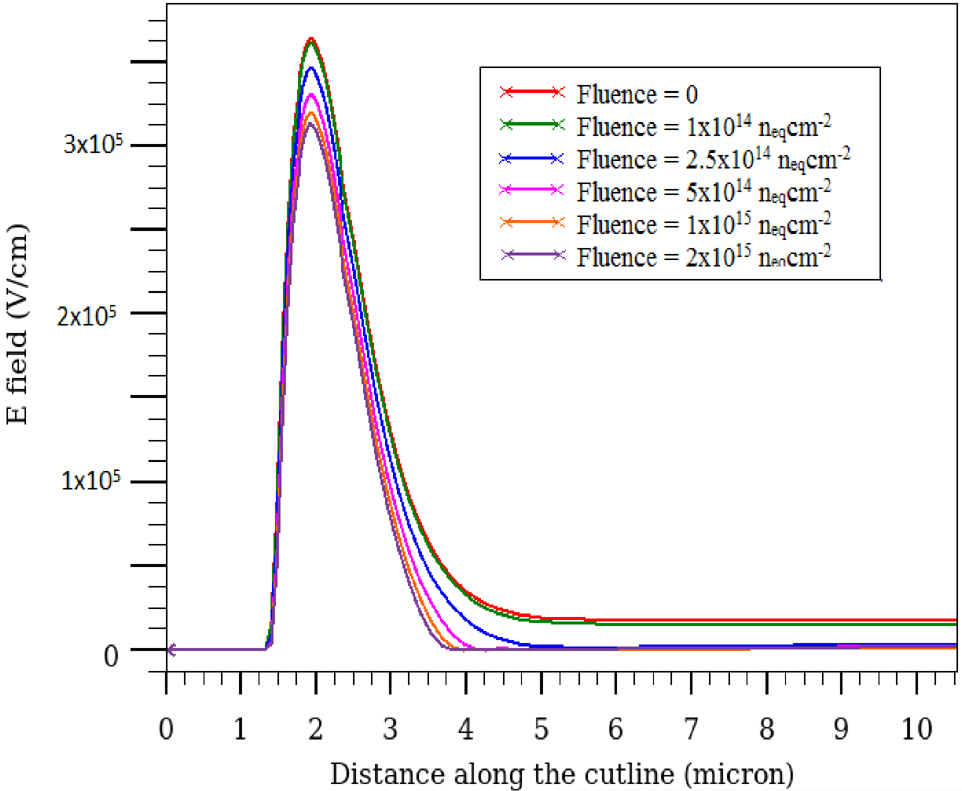
Fig. 10. Measured absolute collected charge as a function of the applied bias for a LGAD sample irradiated to different fluences.

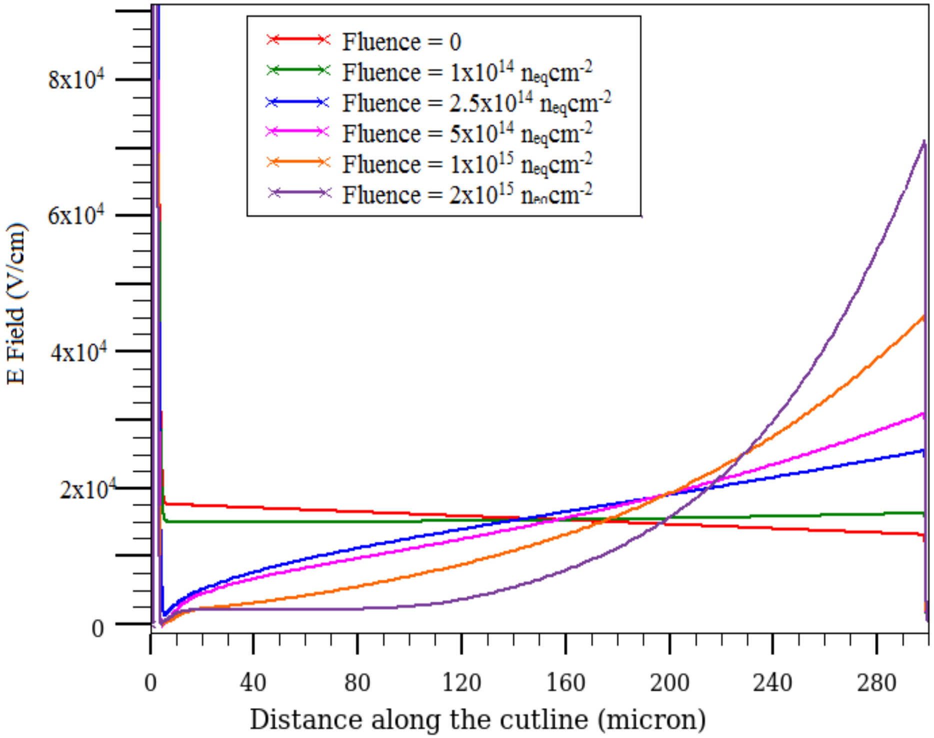
G. Pellegrini, Hiroshima 2014, NIMA

Good qualitative agreement with measurements !

(Remember : we don't know the LGAD doping profile)

Irradiation effect on electric field inside LGAD



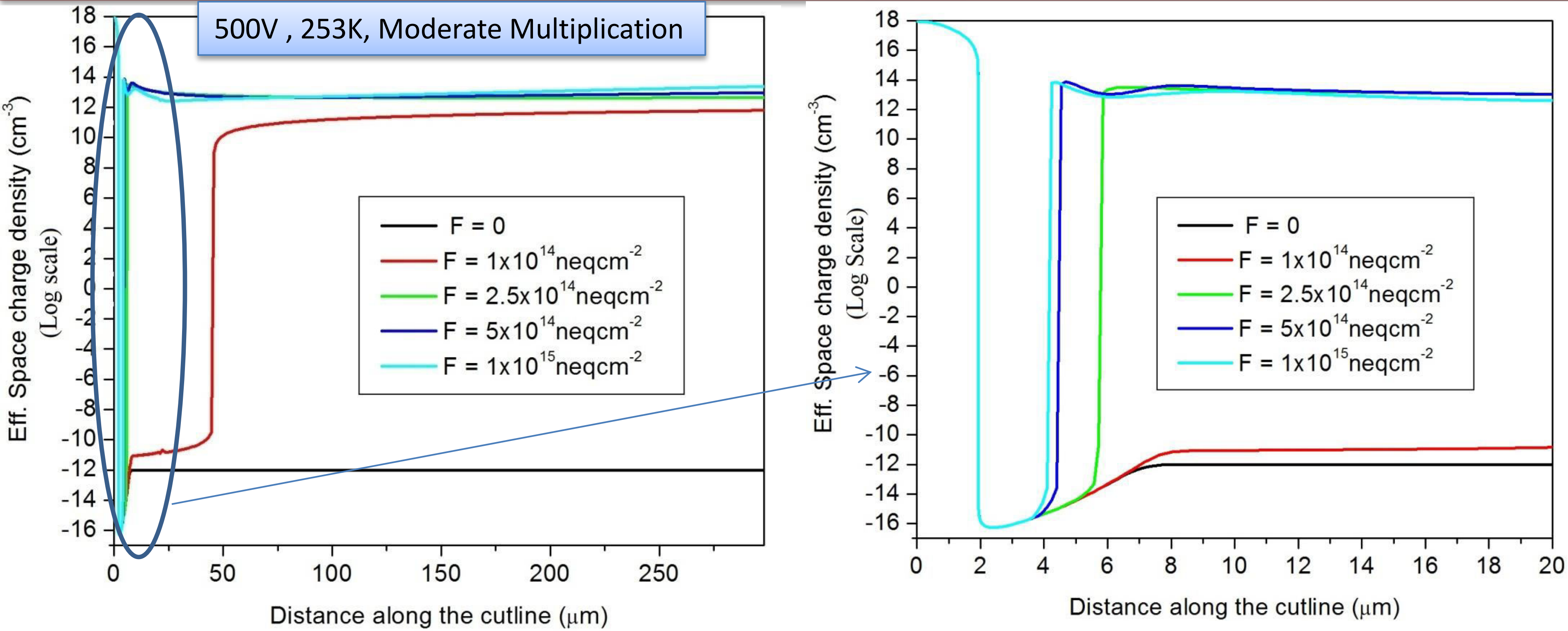


Medium Multiplication case, 500V, 253K

- Peak field inside p-well is lowered with increasing irradiation fluence
    - Width of multiplication region is also reduced
- Electric field just below p-well is strongly affected (lowered!) with irradiation
    - Would lead to inefficient charge collection
- Backside electric field peak grow with fluence
- Since additional donor traps are introduced for charged hadron*, MF lowering will be faster for charged hadron (as backside field will be higher)

*NIM A 611 (2009) 52–68

Effective space charge variation with fluence


500V , 253K, Moderate Multiplication

Effective space charge density = (n+ Conc. + Ionized Donor trap Conc.) – (Boron Conc. + Ionized Acceptor trap Conc.)

Space charge density inside bulk and multiplication regions are affected by irradiation traps

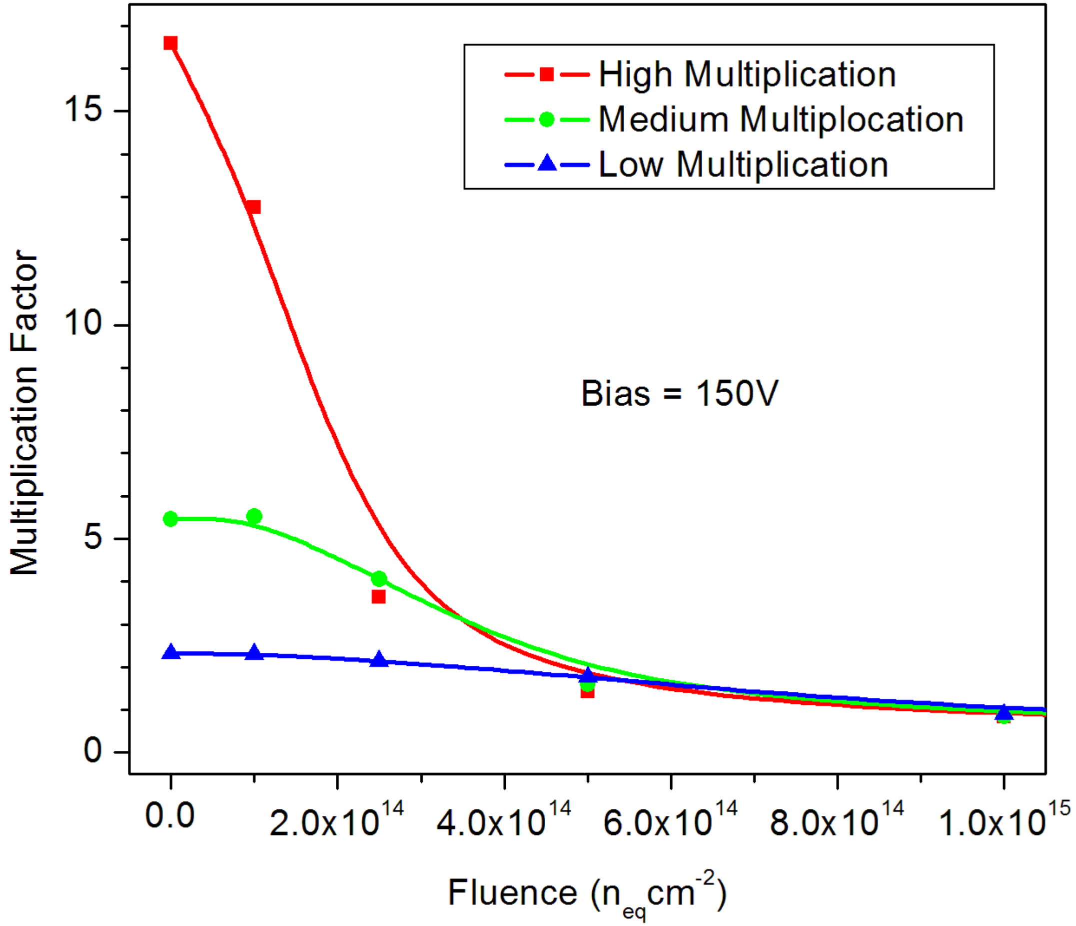
- *Bulk is type-inverted by positive space charge of donor traps*
- *Even effective space charge inside multiplication region is significantly affected*

The width of Multiplication region is reduced with fluence

- Results in lower field, and hence, lower multiplication

Traps Effect appears as Acceptor Removal !

MF variation for 150 µm thick LGAD structure



- MF decreases with fluence for thinner LGAD designs too
- Somewhat higher MF for thinner sensors, after mid-ranged fluence irradiation (around $5 \times 10^{14} n_{eq} cm^{-2}$)

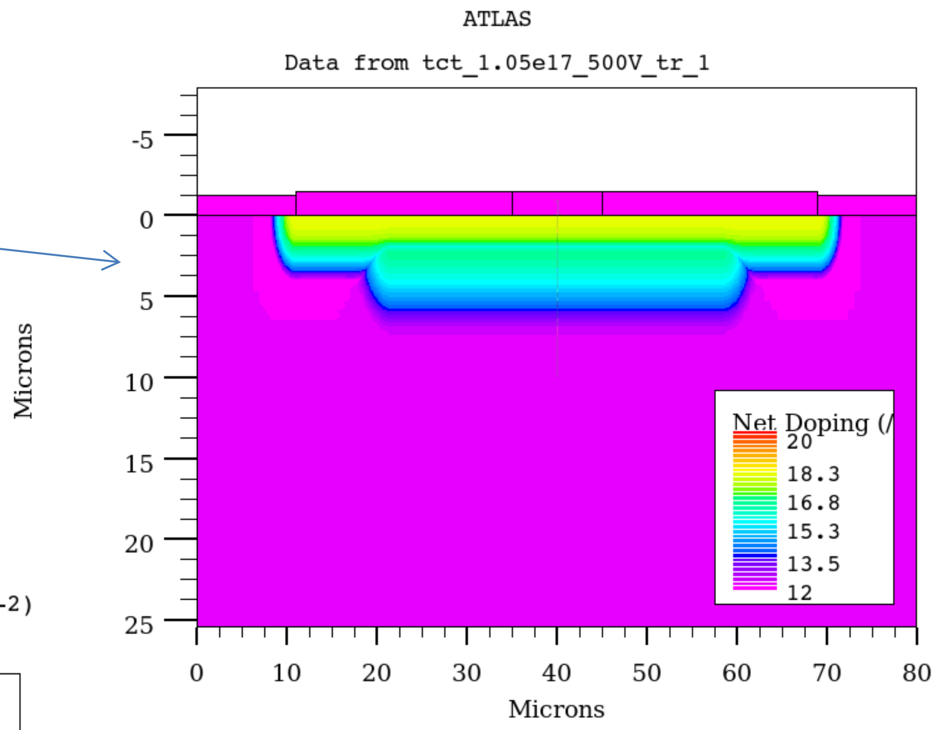
Summary and conclusions

- Charge multiplication factor is dependent on both p-well and n^+ doping profiles
    - n^+ and p-well doping profiles must be tuned vary carefully
- Charge multiplication factors decrease with irradiation fleuence
    - Model developed during HPK campaign used for simulations
    - No additional parameter/assumptions were made
    - No acceptor removal assumed
    - Simulated trend are very similar to measured one
- Practically, there is no Charge multiplication for LGAD irradiated with fluence above $5\text{x}10^{14}\ n_{eq}cm^{-2}$
- Similar lowering of MF with fluence is observed for thinner LGAD structures
- LGAD MF degradation appears to be due to trap effects only
- Since MF lowering with fluence is due to the acceptor & donor traps, the LGAD MF degradation would not be improved by use of Gallium implantation, instead of Boron for p-well
- Would like to carry out simulations for actual LGAD doping profiles (if available!)

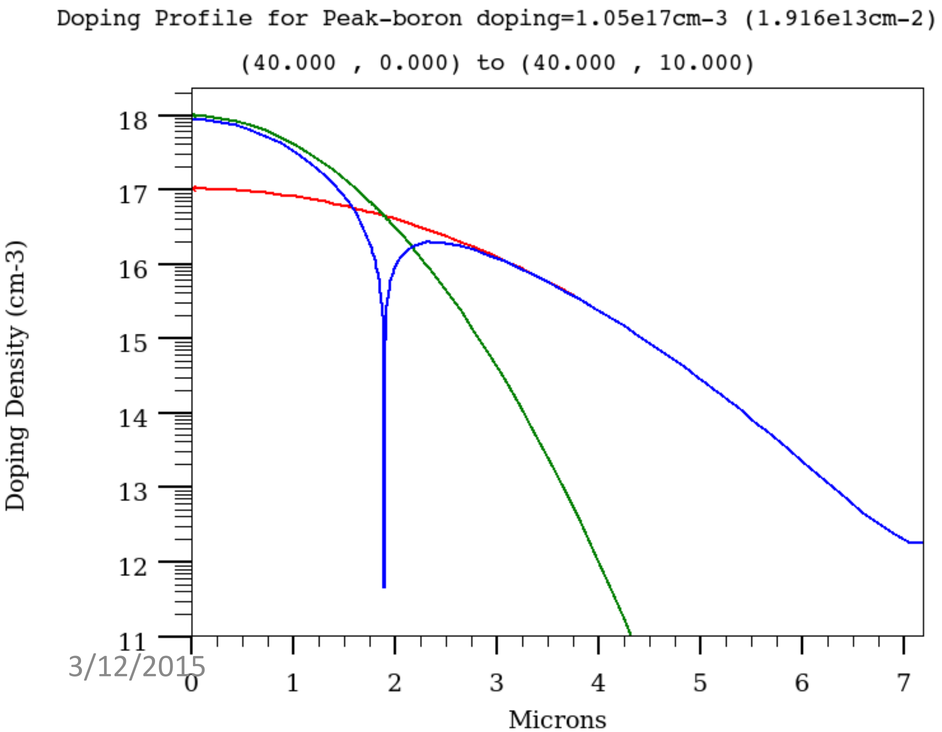
Backup

LGAD simulation structure for Breakdown

Strip type LGAD design was used

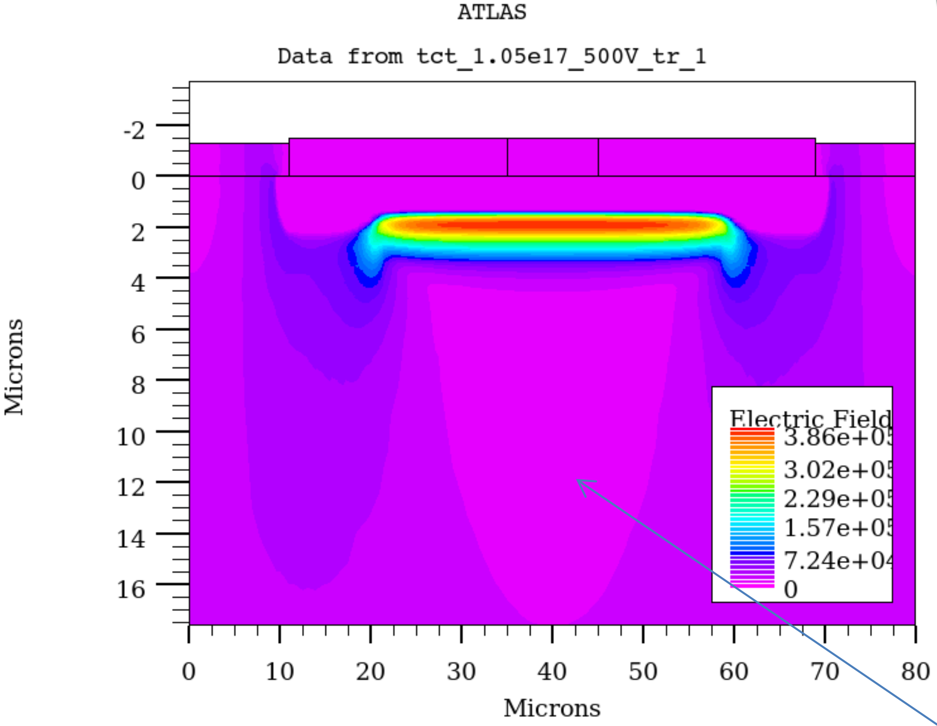

ATLAS

Data from tct_1.05e17_500V_tr_1

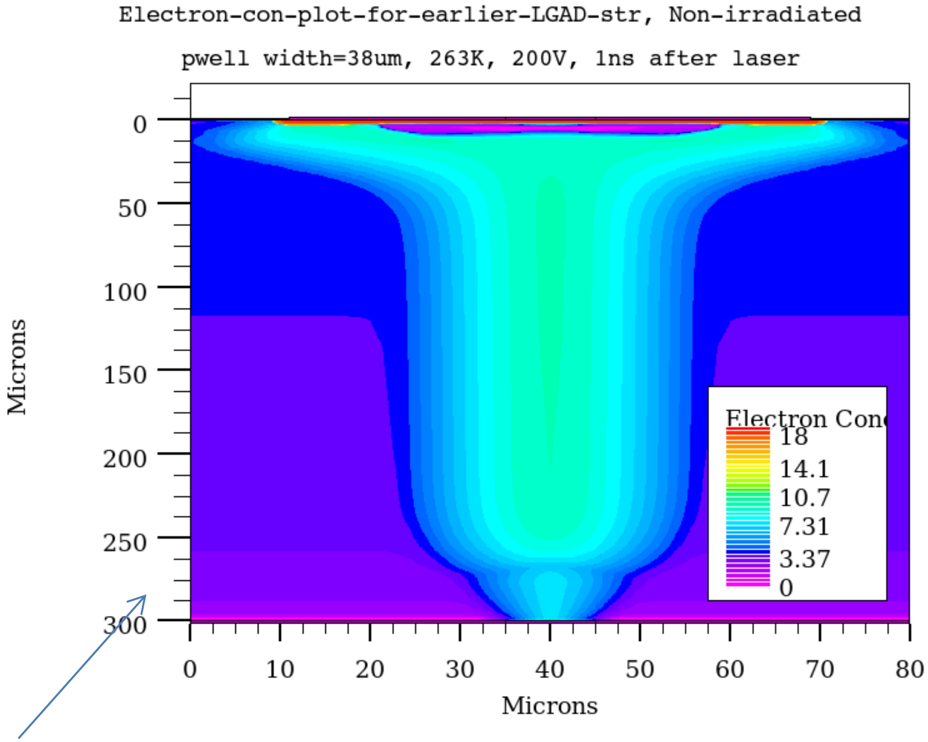

Doping Profile for Peak-boron doping=1.05e17cm-3 (1.916e13cm-2)

(40.000 , 0.000) to (40.000 , 10.000)

E field contours


ATLAS

Data from tct_1.05e17_500V_tr_1

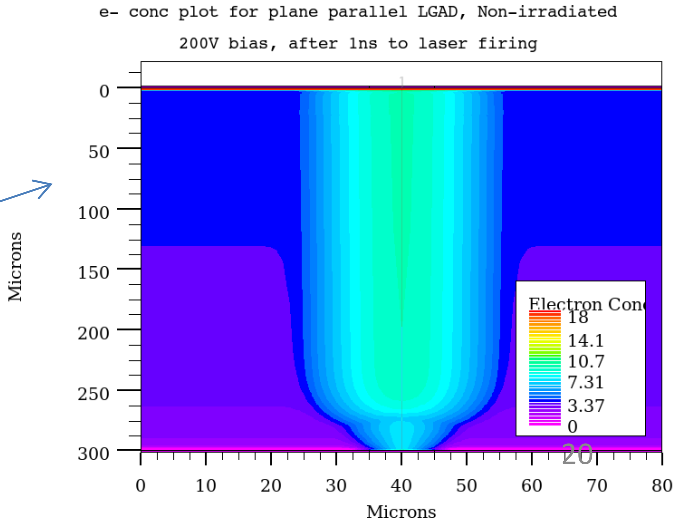

Electron-con-plot-for-earlier-LGAD-str, Non-irradiated

pwell width=38um, 263K, 200V, 1ns after laser

E field contours and electron flow for strip-type LGAD

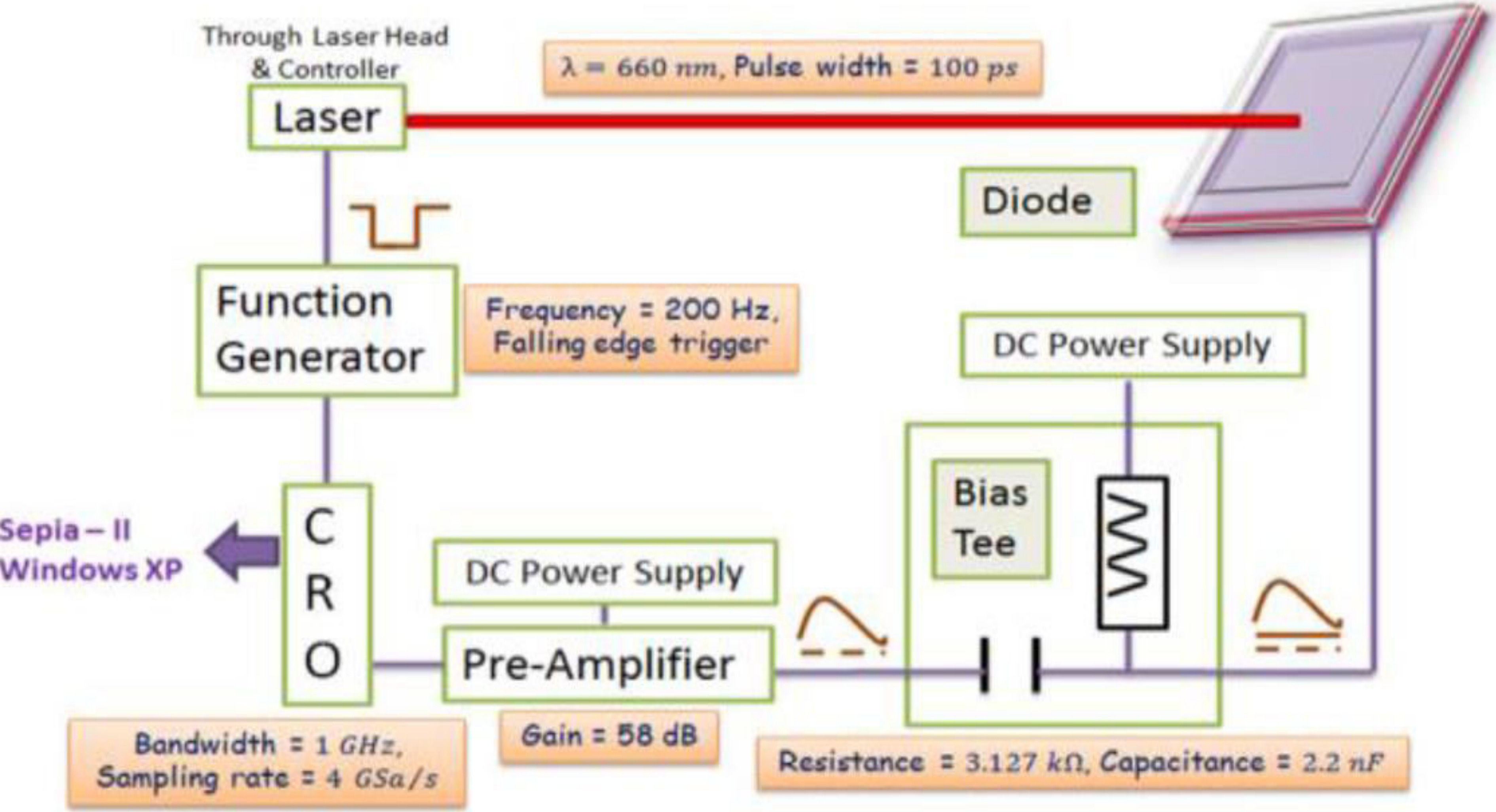
- Gave much lower MF for non-irradiated LGAD as most of electrons are by-passing the multiplication region

Electron flow for plane-parallel LGAD designs used for the present simulations


e- conc plot for plane parallel LGAD, Non-irradiated

200V bias, after 1ns to laser firing

TCT set up DU



Through Laser Head & Controller

Laser

$\lambda = 660\ nm$, Pulse width = $100\ ps$

Diode

Function Generator

Frequency = 200 Hz, Falling edge trigger

DC Power Supply

Bias Tee

Sepia – II Windows XP

CRO

DC Power Supply

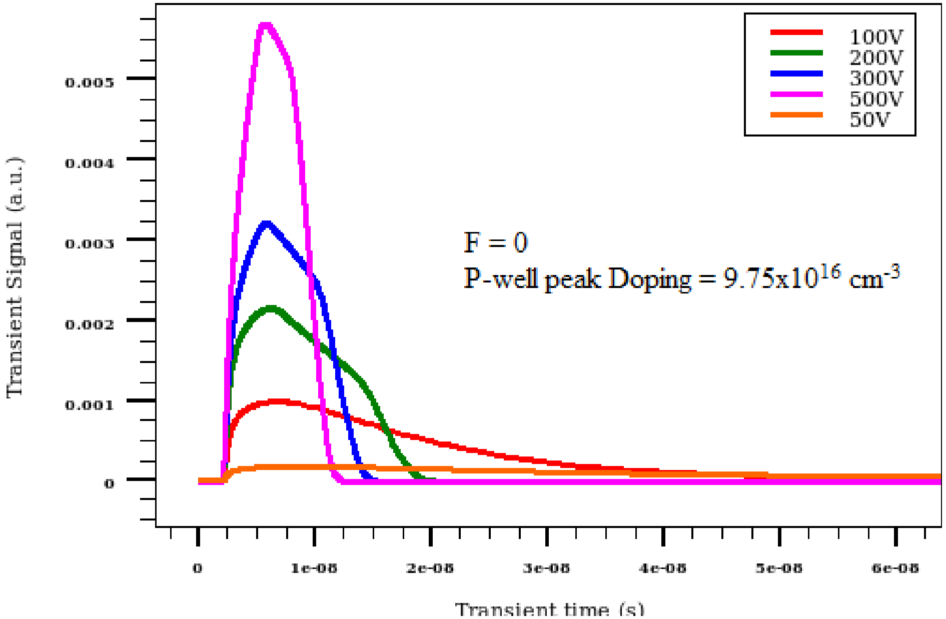
Pre-Amplifier

Bandwidth = $1\ GHz$, Sampling rate = $4\ GSa/s$

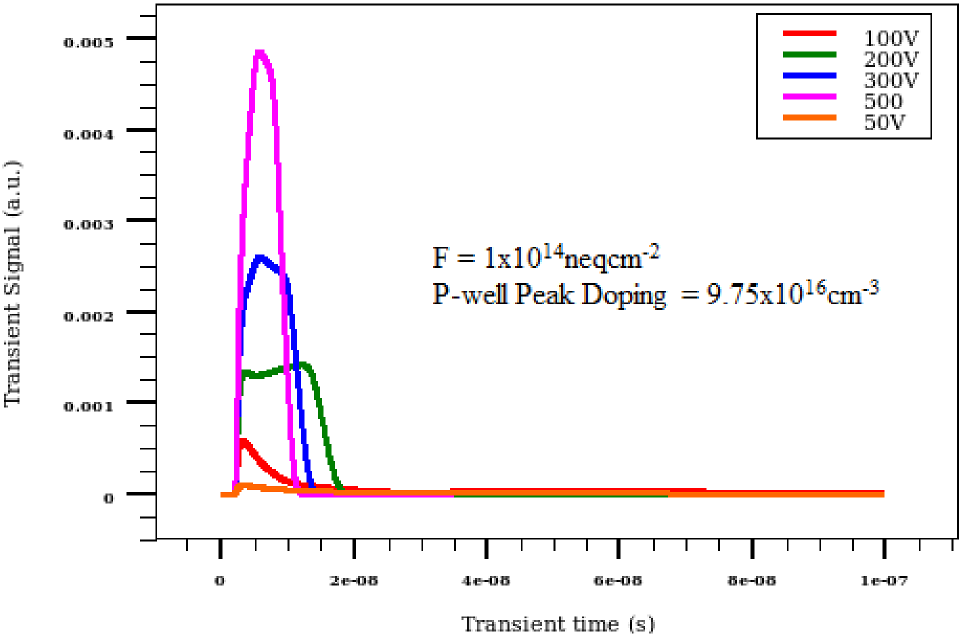
Gain = 58 dB

Resistance = $3.127\ k\Omega$, Capacitance = $2.2\ nF$

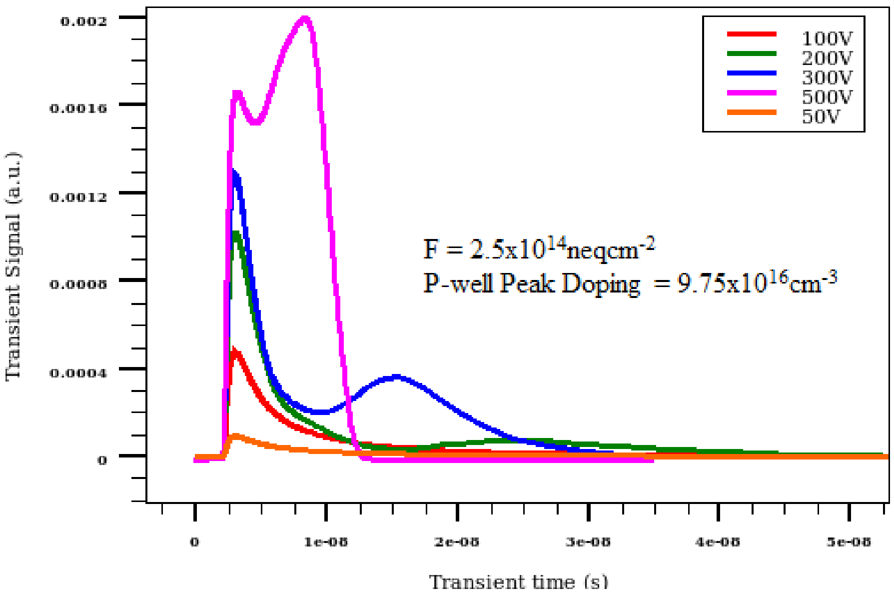
Simulated TCT pulse for moderate multiplication case



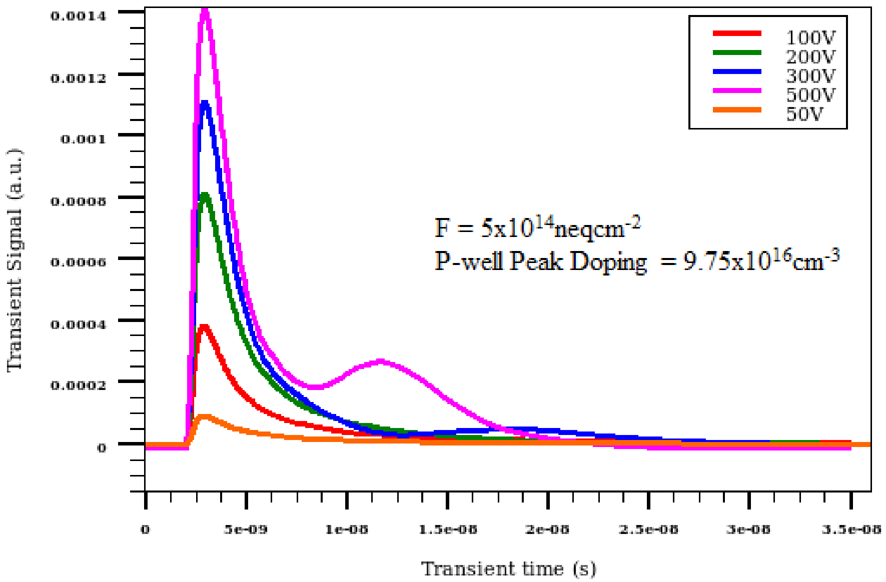
F = 0
P-well peak Doping = 9.75x10^{16} cm^{-3}



F = 1x10^{14}neqcm^{-2}
P-well Peak Doping = 9.75x10^{16}cm^{-3}

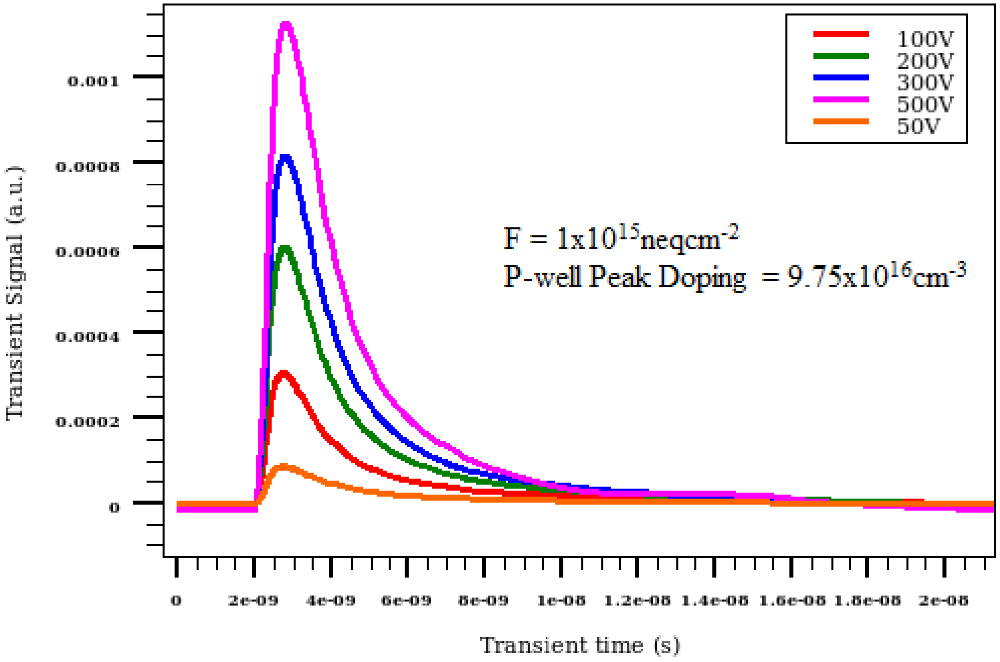


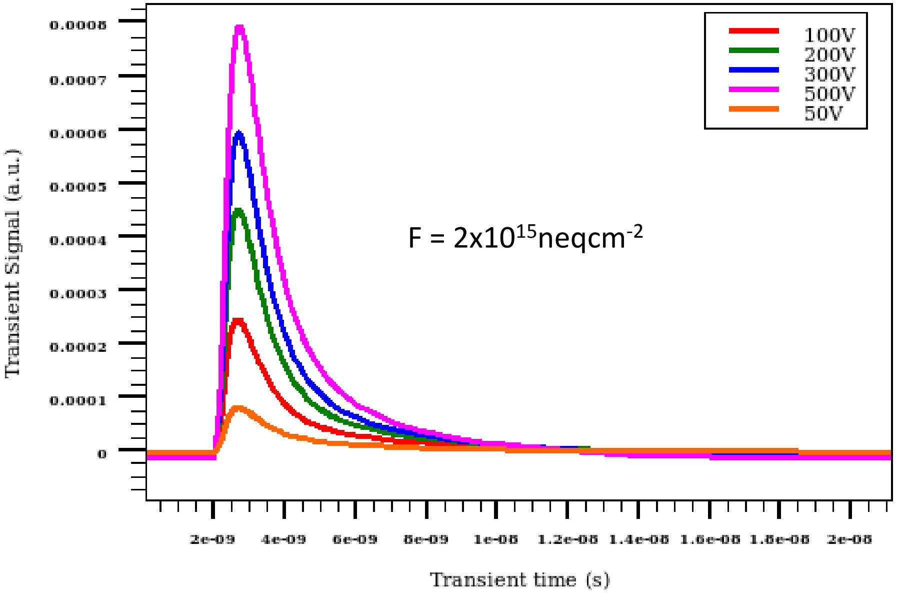
F = 2.5x10^{14}neqcm^{-2}
P-well Peak Doping = 9.75x10^{16}cm^{-3}



F = 5x10^{14}neqcm^{-2}
P-well Peak Doping = 9.75x10^{16}cm^{-3}

Simulated TCT pulses





No second peak (due to multiplication) for fluence 1e15 and 2e15 neqcm^{-2}