TCT in presence of DC illumination

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Why would you do that?

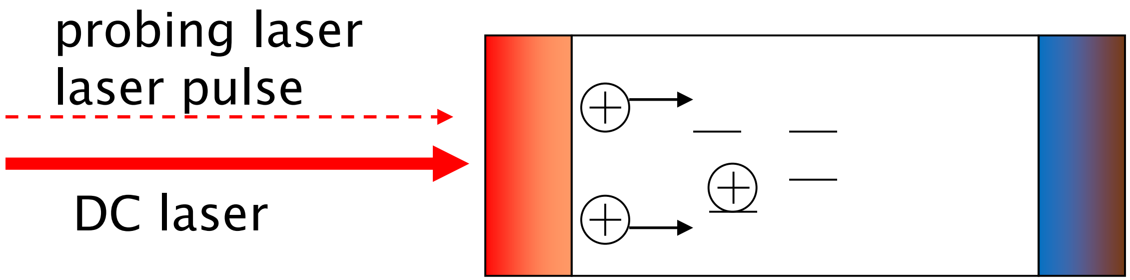
- In irradiated detectors deep trap occupation probability can be changed injection of certain carrier type (the story of RD39)

- Injection can therefore manipulate space charge and one can derive the properties of traps responsible for changing device properties

- Recently a question of what is mechanism of “effective acceptor removal” has been of interest in the detector community.

Can the operation of LGAD detectors under DC illumination reveal the nature of the defects responsible of “effective acceptor removal”.

TCT in presence of DC illumination



$$p = \frac{\Delta I}{S\, v_h\, e_0}$$

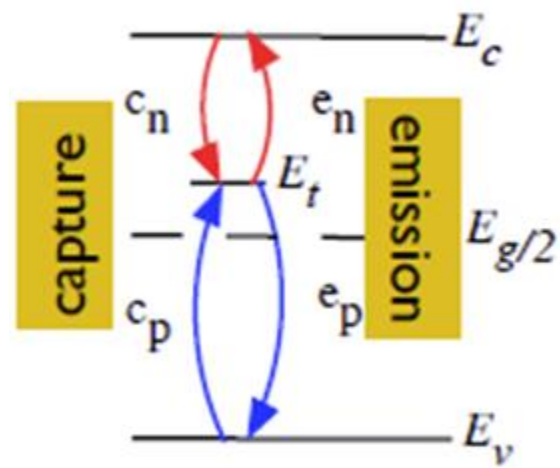
- ΔI ← Increase of leakage current due to illumination
- v_h ← drift time of holes through the detector

N_{eff} controlled by:

- illumination intensity (p)
- operation voltage (p)
- temperature
(trapping –detrapping process)

Occupation Probability of the trap →

$$P_t = \left[\frac{c_p p + c_n n_i \exp(\frac{E_t - E_i}{k_B T})}{c_n n + c_p n_i \exp(\frac{E_i - E_t}{k_B T})} + 1 \right]^{-1}$$



Influence of DC on space charge

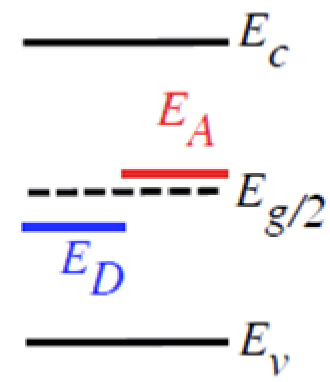
$$N_{eff} = \sum_{donors} N_t(1-P_t) - \sum_{acceptrors} N_t P_t$$

$P_t \sim 1$ for traps $E_t < E_i$ $\quad (E_i \approx E_g/2)$

$P_t \sim 0$ for traps $E_t > E_i$

$0 < P_t < 1$ changes only few kT around midgap

The reason for TCAD modeling

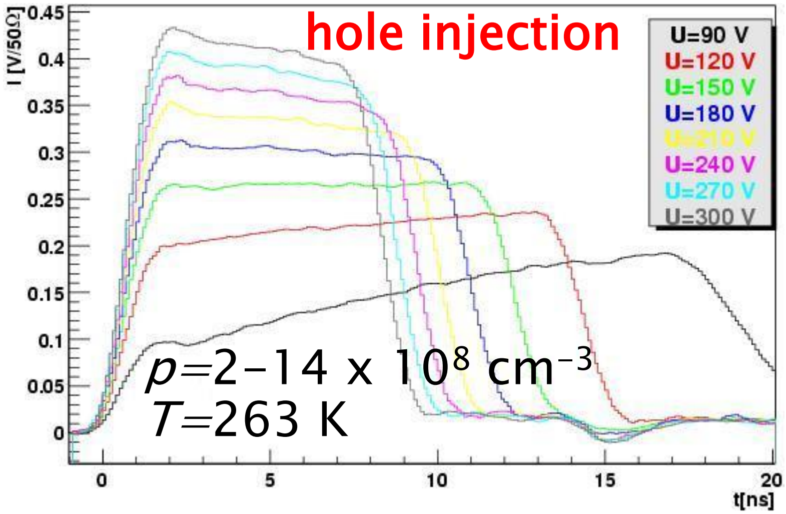


$$P_t = \left[\frac{c_p p + c_n n_i \exp(\frac{E_t - E_i}{k_B T})}{c_n n + c_p n_i \exp(\frac{E_i - E_t}{k_B T})} + 1 \right]^{-1}$$

p and n should be comparable to n_i and $E_t \sim E_i$ to have and effect

Example of space charge change

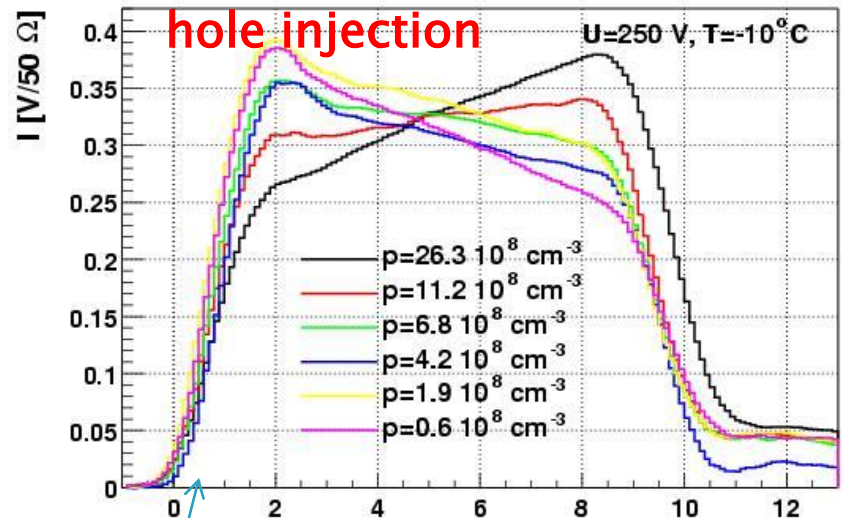
Detectors irradiated with neutrons FZ p-n 15 kΩcm (V_{fd}~20 V)



p=2–14 x 10^8 cm^{-3}
T=263 K

Φ_{eq}=5 x 10^{13} cm^{-3}

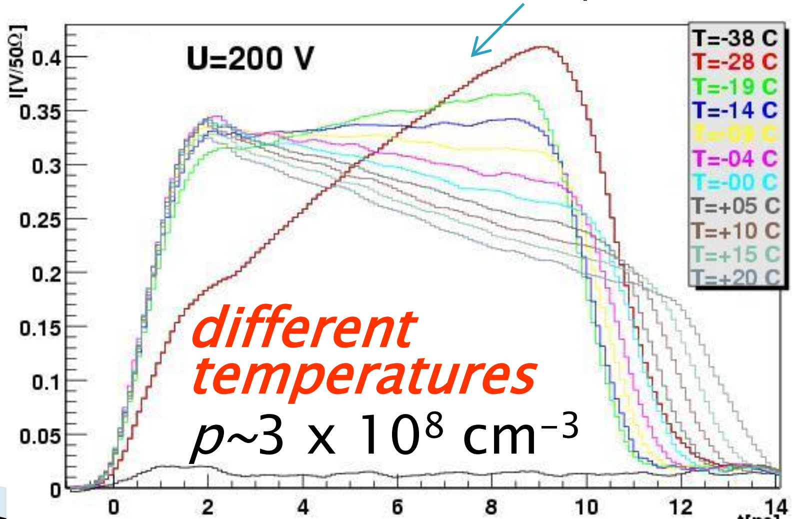
different voltages



Φ_{eq}=7.5 x 10^{13} cm^{-3}

different light intensities

N_{eff} can be estimated from the slope of the signal!



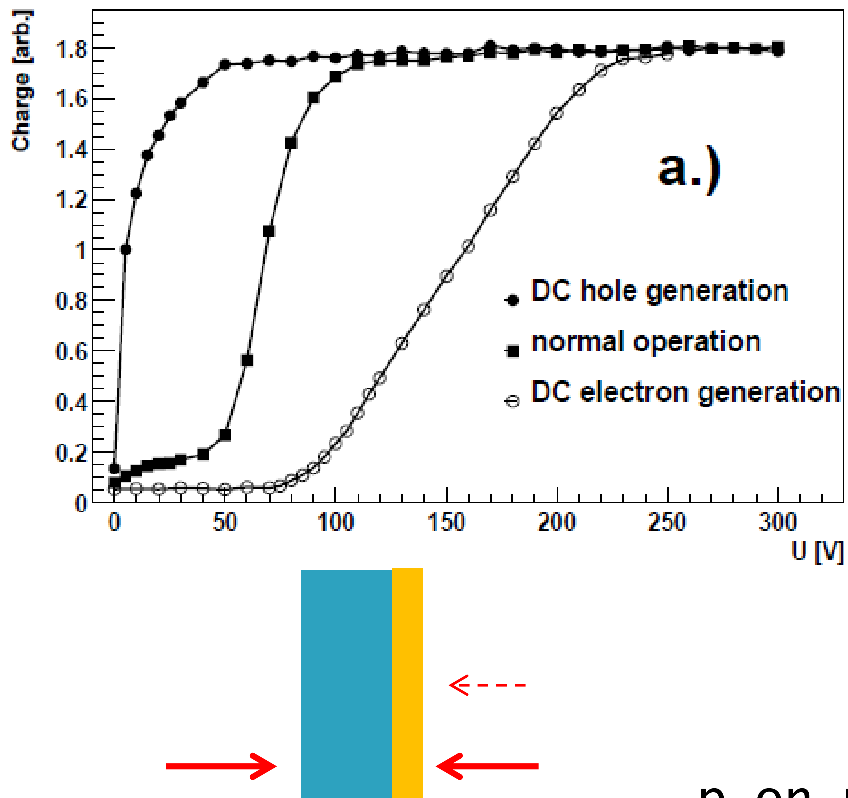
different temperatures

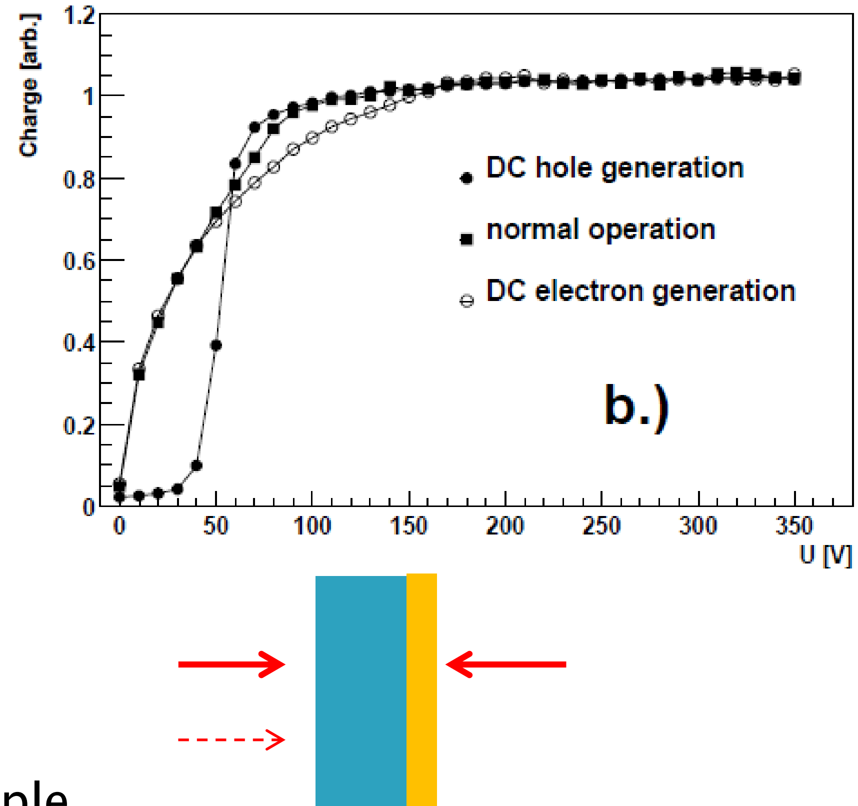
p~3 x 10^8 cm^{-3}

G. Kramberger, TCT in presence of DC illumination, 2nd TCT workshop, Ljubljana

Example of space charge manipulation

Changes in Q-V indicate nicely the space charge





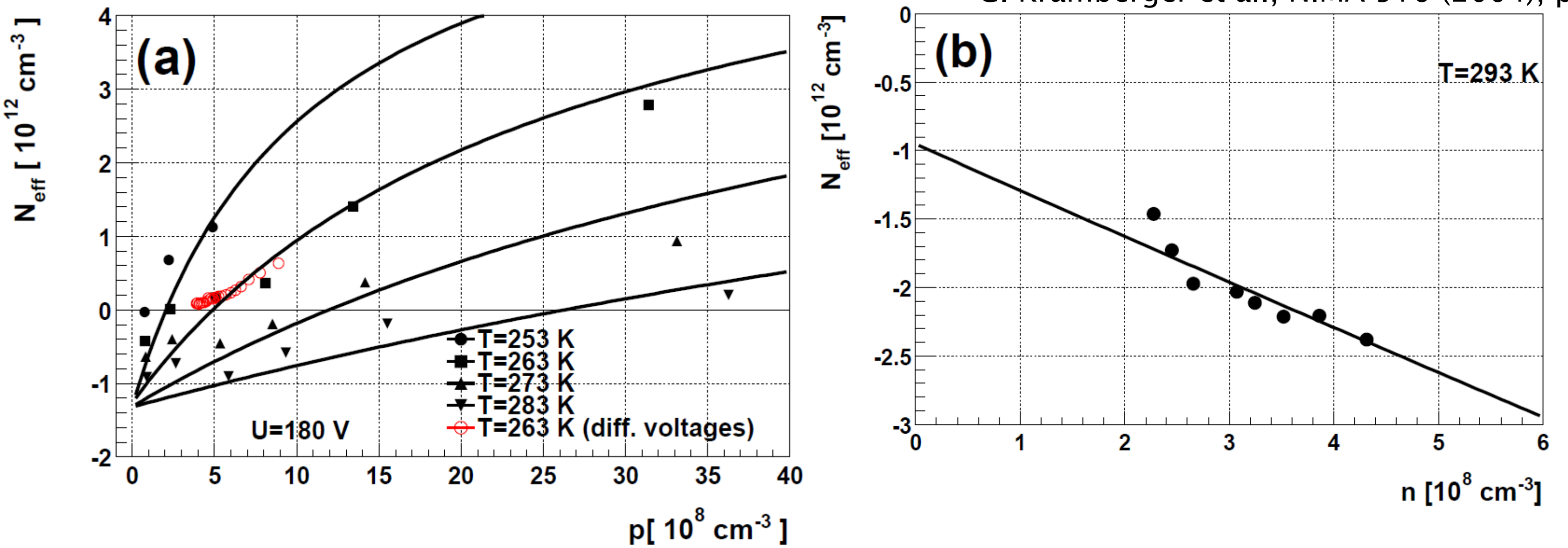
p-on-n sample

Φ_{eq}=5 x 10^{13} cm^{-3} at 263 K

The effect of p,n on space charge

Φ_{eq}=5 x 10^{13} cm^{-2}

G. Kramberger et al., NIMA 516 (2004), p. 109-115.



- Changes of N_{eff}(p,n) are assumed to be linear with fluences

$$N_{eff}(p=3\cdot10^{9}\,\mathrm{cm}^{-3})-N_{eff}(p=0)\approx+0.08\,\mathrm{cm}^{-1}\cdot\Phi_{eq}$$ @263 K (100 x larger current)

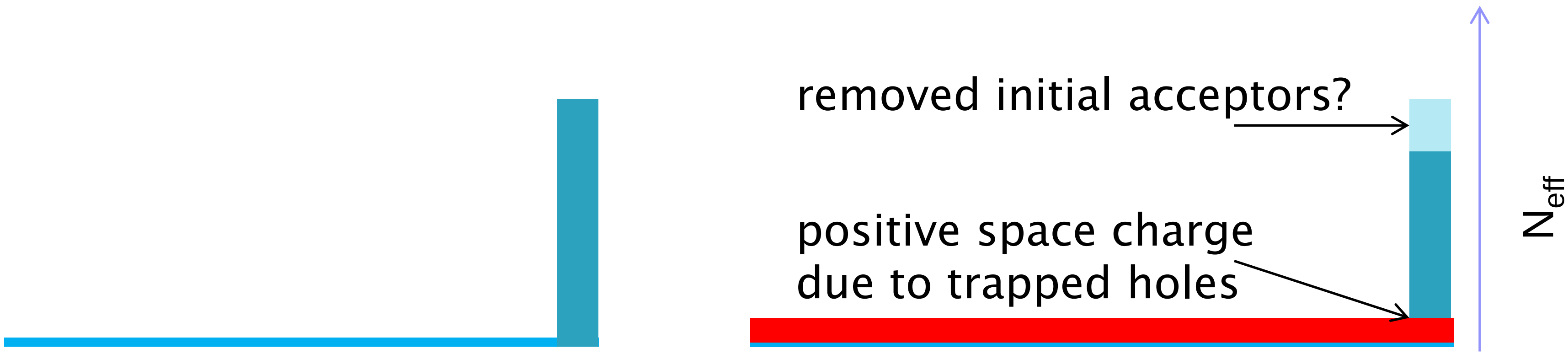
$$N_{eff}(n=3\cdot10^{8}\,\mathrm{cm}^{-3})-N_{eff}(n=0)\approx-0.02\,\mathrm{cm}^{-1}\cdot\Phi_{eq}$$ @293 K

n_i=6.6e8 (263 K), 8.69e9 (293K) cm^{-3}

At Φ_{eq}=10^{14} cm^{-2} → ΔN_{eff}~max. 10^{13} cm^{-3}

Origin of effective acceptor removal

- Can we exploit the same technique to determine the origin of gain drop in LGAD detectors – TCAD simulations can explain it to some extent without it



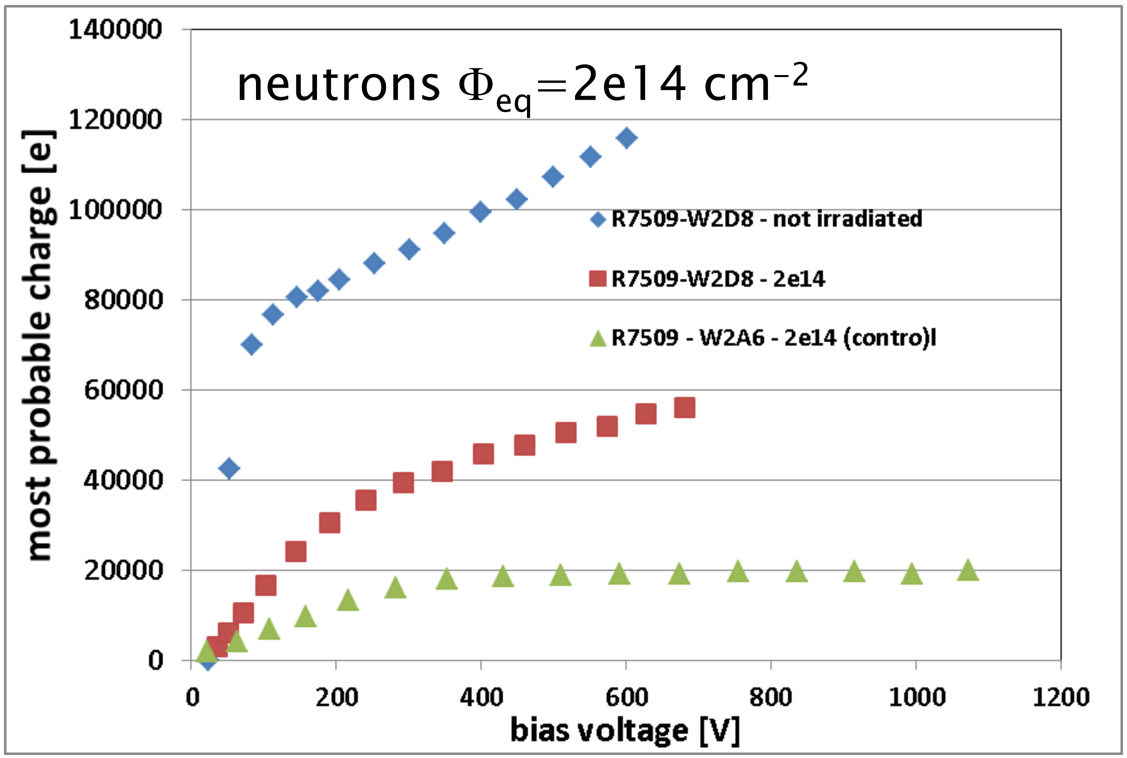
The gain at very high voltages ($V_{bias} >> V_{fd}$) is reduced due to: initial acceptor (boron) removal or/and but also due to space charge from deep traps which compensate the negative space charge from Boron:

- Boron insensitive to concentration of free carriers in the bulk
- Deep traps sensitive to free hole and electron concentrations

Gain drop in irradiated LGAD detectors

Requirements for good probing:

- fluence small enough to see a clear contribution from holes in TCT signal
- still a sizeable difference in gain to a non-irradiated detector
- measured also with ^{90}Sr to estimate the absolute charge

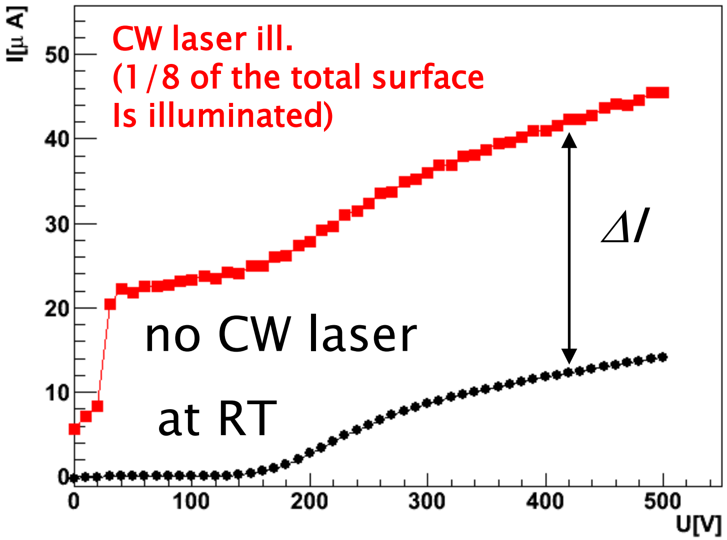


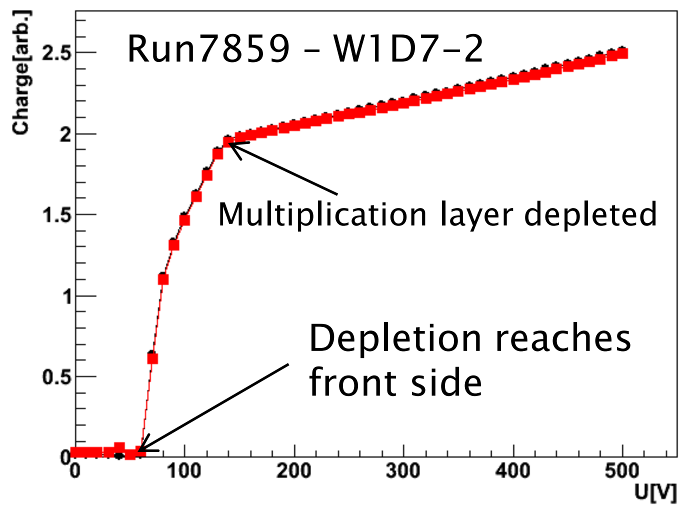
Investigated:
Run7509 – neutrons
Run6474 – pions
(not shown here)

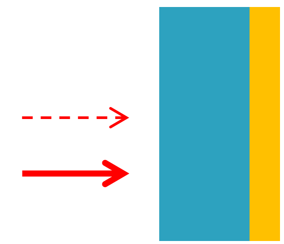
$$G = \frac{Q_{LGAD}}{Q_{PIN}}$$

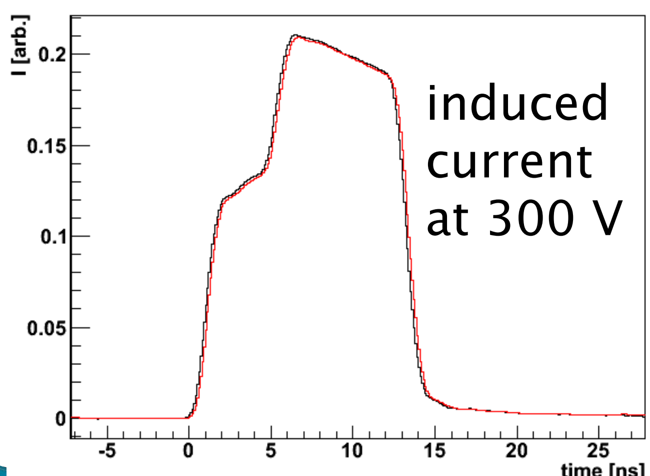
Non-irradiated detector (LGAD run 7859)

Back illumination (electron injection)







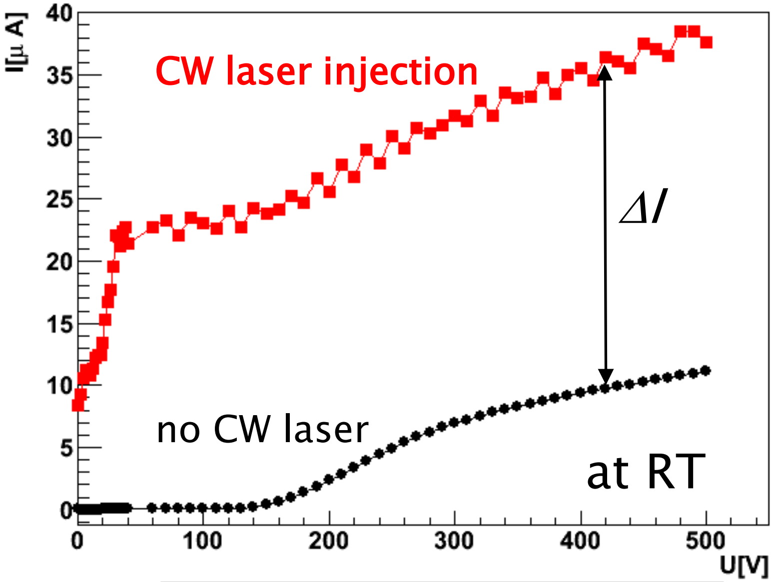


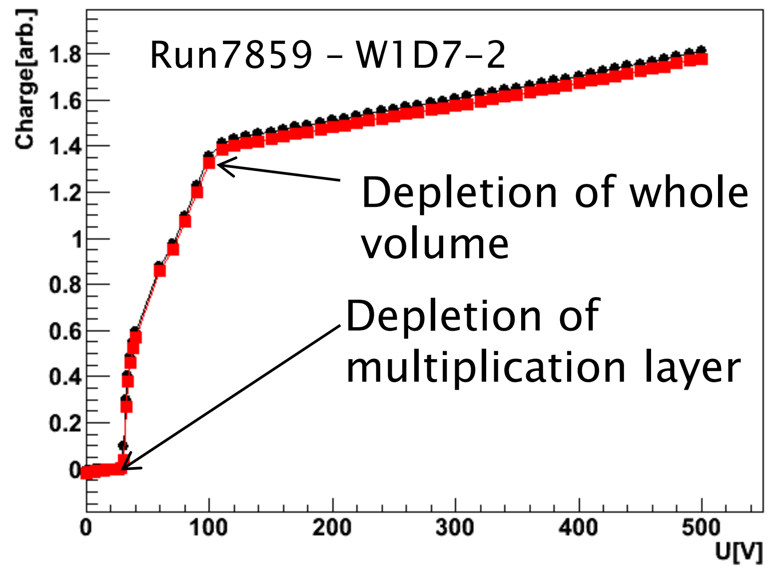
<u>No change</u> in both collected charge and electric field (deduced from the induced current shape) after large injection of electrons by DC light illumination!

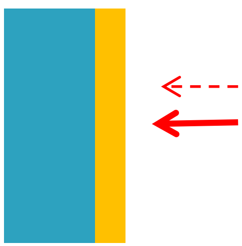
No deep ELECTRON traps present before irradiation!

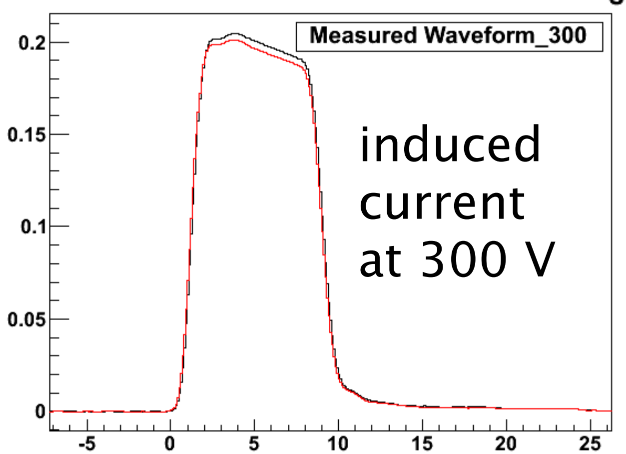
Non-irradiated detector (LGAD run 7859)

Front illumination (hole injection)







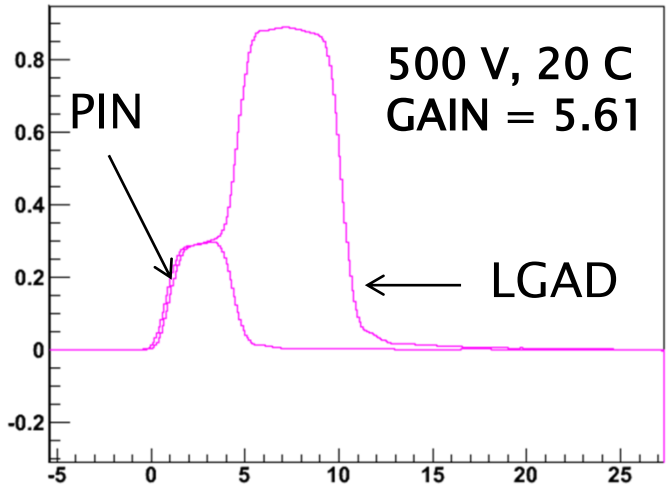


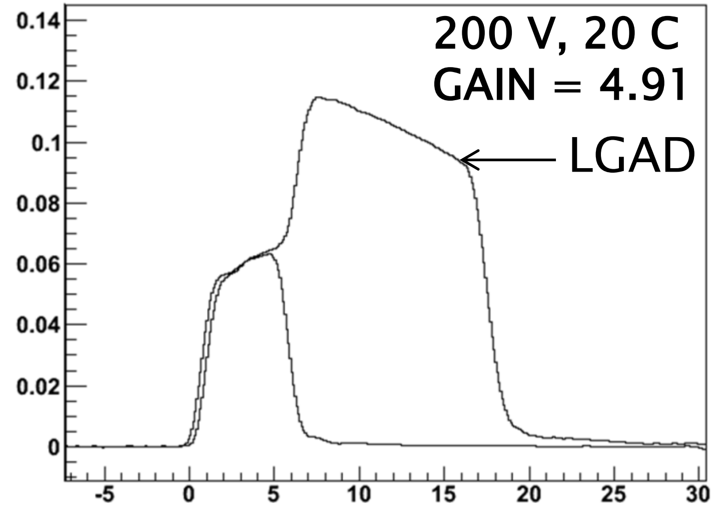
No change in both collected charge and electric field (induced current shape) after large injection of electrons by DC light illumination!

No deep HOLE traps present before irradiation!

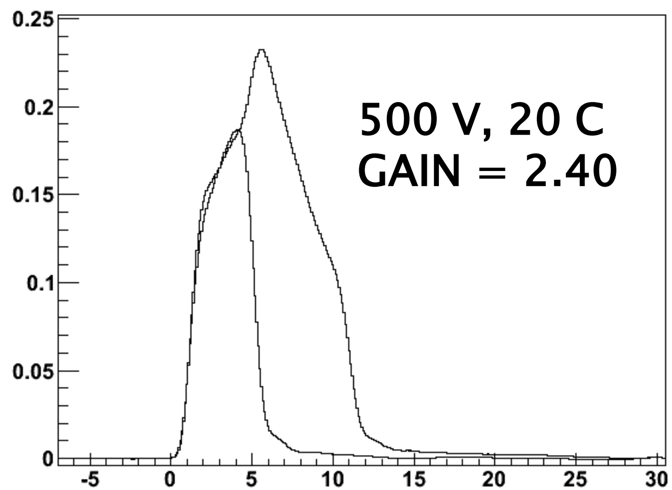
TCT – back illumination and loss of gain

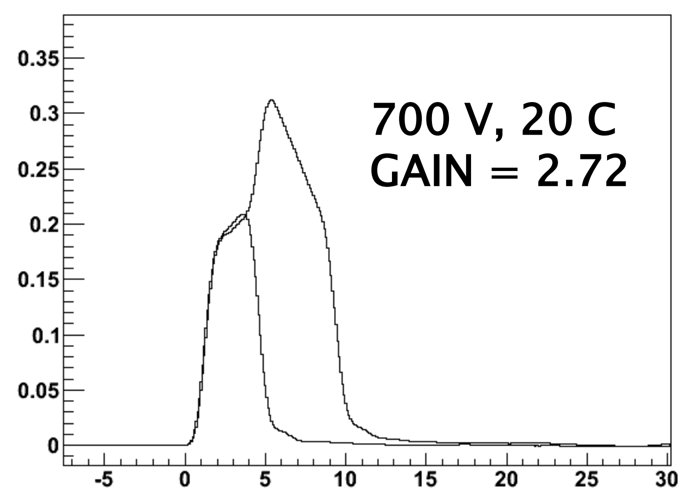
Non-irradiated PIN and LGAD induced currents





Irradiated (2e14 cm^{-2}) PIN and LGAD induced currents

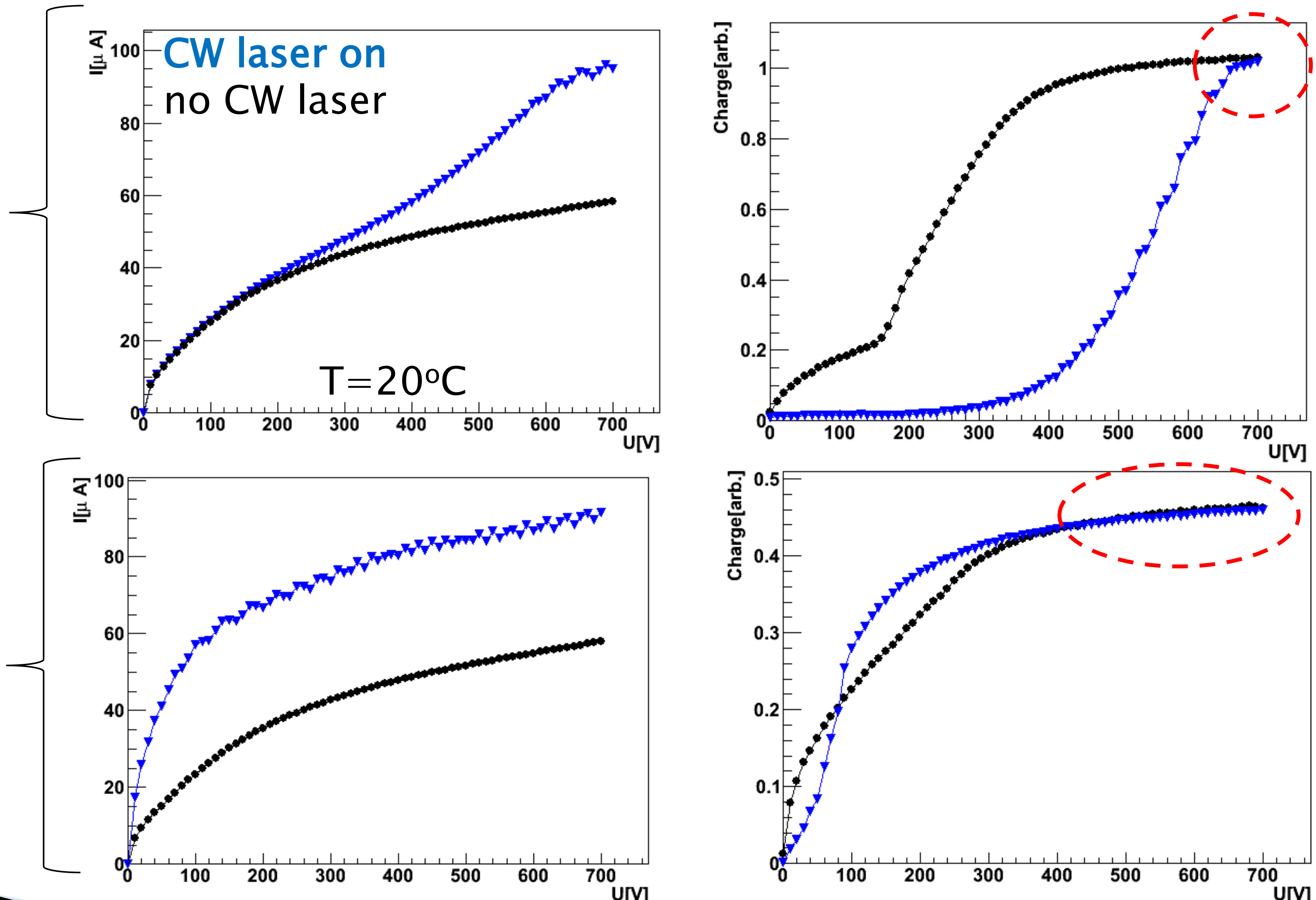




Control sample irradiated to 2e14 cm^{-2}

Electron injection (back illumination)

Hole injection (front illumination)

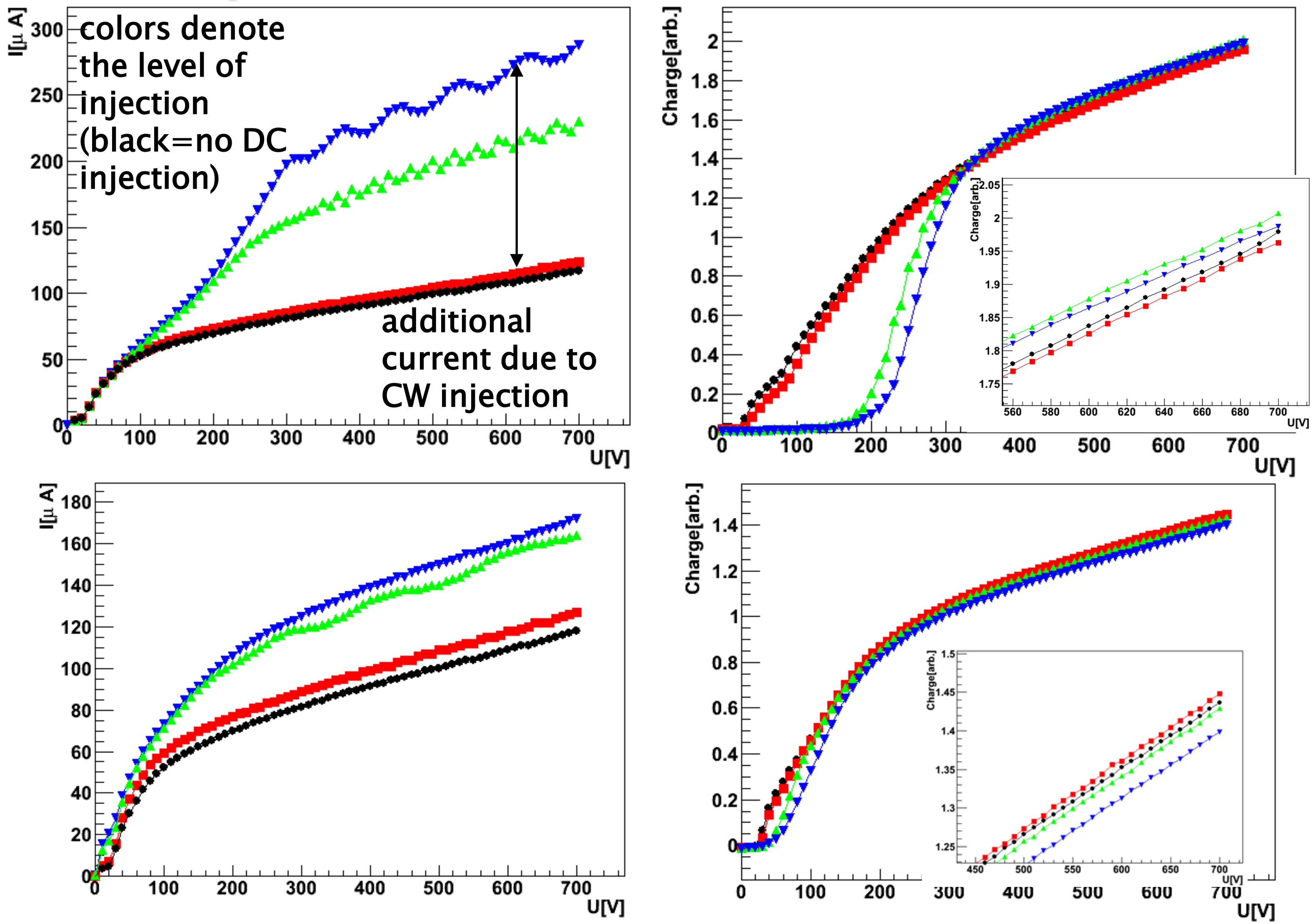


Electric field changes, but not the charge at high V_{bias}!
Trapping very weakly affected by additional *p,n* concentration.

LGAD sample irradiated to 2e14 cm^{-2}

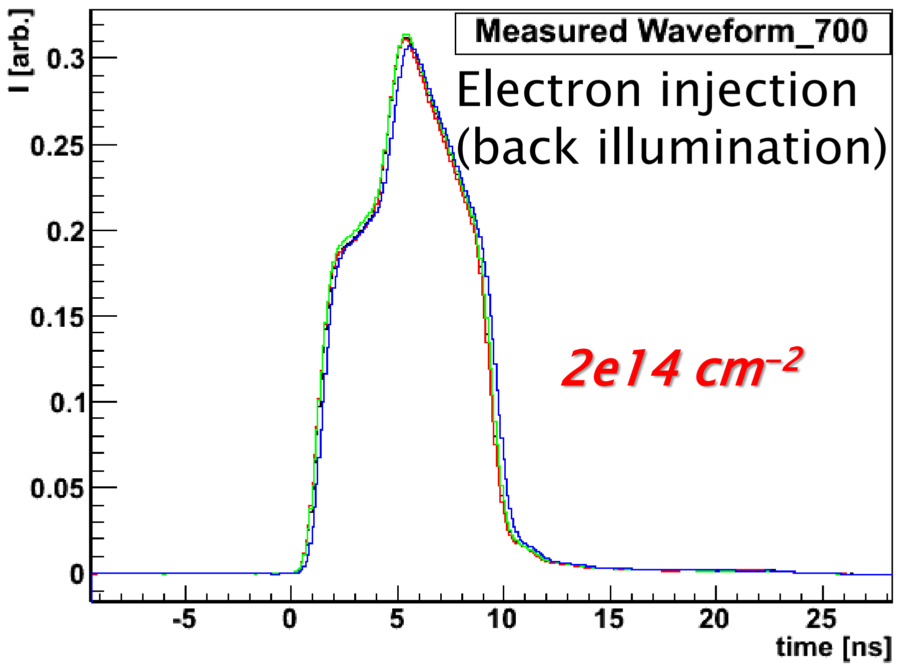
Electron injection (back illumination)

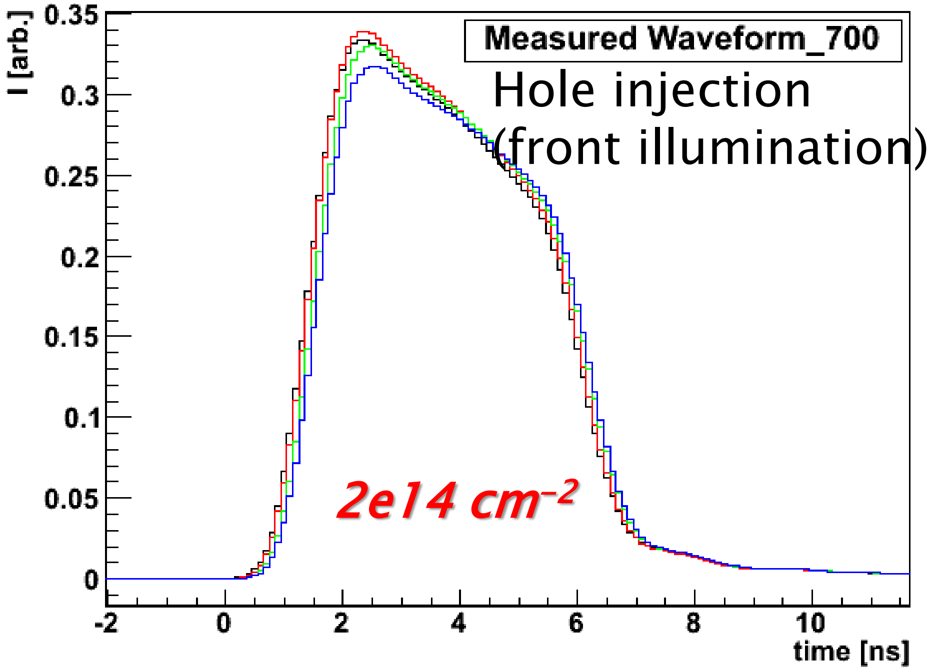
Hole injection (front illumination)



- Once the sensor is depleted -> gain reflects the difference in $N_{deep}(p,n)+N_B$.
- At high bias voltages the charge changes with light intensity by max few percent.

TCT – induced currents for LGAD





- No difference in induced current pulse shapes at high bias voltages for different DC illumination levels for electron injection
- Small difference in induced current for hole injection at the highest intensity – trapped holes moderate the bulk, but have little effect on doping concentration of p^+ layer
- Similar conclusions for pion irradiated samples (not shown)

Discussion

- At Φ_{eq}=1e14 cm^{-2} the maximum change of ΔN_{eff}=10^{13} cm^{-3} compared to LGAD doping of >10^{15} cm^{-3} very small change of N_{eff} is possible – not enough to change the gain for factor of two.

- As soon as the detector is depleted the gain is almost independent on free carrier concentration and bias voltage.
  - We see large decrease in N_{eff}(electric field in multiplication zone).
  - $N_{eff}=N_{deep}(p,n)+N_B$ -> without acceptor removal N_{deep} should be highly affected by n,p , but this is not observed…
  - Trapping affects the signal, but CCE measurements point to max 10%.

Conclusions

- DC illumination is a very powerful tool to change occupation probability of deep traps and observe changes in macroscopic properties by TCT

- For the free hole concentration of almost order of magnitude higher than n_i the introduction rate of positive space charge is around 0.08 cm^{-1}

- Using DC illumination TCT on LGAD showed:
  - Before irradiation the signal is unaffected by DC illumination both for hole and electron injections.
  - For irradiated LGADs the loss gain is attributed to decrease of N_{eff} due to removal of shallow boron rather than deeps traps (no effect on gain from changing illumination after full depletion voltage)