Determination of impact ionization parameters for low gain avalanche detectors produced by HPK

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Motivation

- Previous determinations of impact ionization parameters for silicon do not work for charge collection measurements obtained via Strontium-90 measurements on LGADs
  - They were obtained on different devices via different methods (e.g. laser carrier injection)
    - Khodin[1], Van Overstraeten[2], Massey[3]
  - Different methods lead to different charge density -> Charge density can impact that gain, thus impact ionization
    - G. Kramberger et al, "Gain dependence on free carrier concentration in LGADs", Nucl. Instrum. Meth. A, vol. 1046, 2023
- Electrons from strontium-90 source are closer to MIPs, making them more relevant to the operation of LGADs in HGTD
- A new model is required that is applicable to LGADs under the conditions they will be tested and operated in
- This presentation is an update of work presented at 39th RD50 workshop(Valencia)
- Impact ionization coefficients are also being investigated by other groups (see Esteban's 40th RD50 talk)
- All results in this talk are published in Jinst (A. Howard *et al* 2022 *JINST* **17** P10036)

[1]Khodin, Alexandre et al. "Silicon avalanche photodiodes for particle detector:: modelling and fabrication." *Nucl. Instrum. Meth. A, vol.* 465, 2001

[2]R. Van Overstraeten et al, "Measurement of the ionization rates in diffused silicon p-n junctions", Solid-State Electronics, Vol. 13, Issue 5, 1970

[3]D.J Massey et al., "Temperature Dependence of Impact Ionization in Submicrometer Silicon Devices", IEEE Transactions on Electron Devices, vol. 53, no. 9, 2006.

Samples

JSI Ljubljana Slovenia

Slovenian Research Agency

- Four wafers from HPK-P2 : 28, 33, 37, & 43
- All samples are
  - 50 µm thick
  - Single pads with 1.3x1.3 mm^2 active area
  - Gain implant is ~2.5 µm deep
- One sensor from each wafer was irradiated to each fluence: 1E14, 4E14, 8E14, 1.5E15, & 2.5E15
  - Only W28 irradiated to 1E14 is missing
- All samples were annealed after irradiation
  - Standard annealing time: 80 mins @ 60˚C
- Charge collection was measured for all sensors using Sr^{90} source
  - see G. Kramberger's talk at 37th RD50 workshop for setup details

Sensor	Fluences $[10^{14}\ cm^{-2}]$	V_{gl} [V]	V_{fd} [V]
HPK-P2 W28	0, 4, 8, 15, 25	54.5, 44.4, 37.1, 29.5, 18.9	61.2, 54.2, 54.2, 59.5, 73.9
HPK-P2 W33	0, 1, 4, 8, 15, 25	53.7, 50.8, 43.2, 36.2, 27.4, 18.9	60.5, 57.3, 53.3, 58.2, 59.0, 60.6
HPK-P2 W37	0, 1, 4, 8, 15, 25	51.4, 48.3, 40.9, 34.5, 24.8, 15.2	57.3, 55.0, 55.2, 54.9, 57.0, 47.8
HPK-P2 W43	0, 1, 4, 8, 15, 25	50.8, 47.8, 41.1, 33.0, 25.1, 13.8	57.3, 57.2, 56.2, 55.5, 57.1, 53.7

V_{gl} & V_{fd} determined from CV measurements at 20˚C

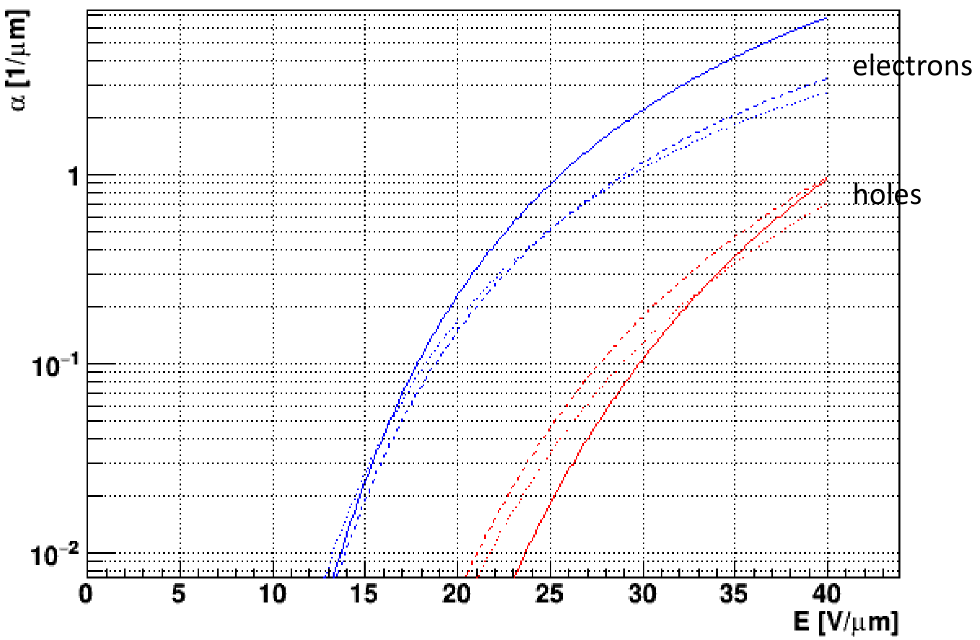
Chynoweth's model

- Chynoweth's model is the most commonly used model -> used as starting point for this study
- It states that the impact ionisation coefficients for electrons, n, and holes, p, is

$$\alpha_{n,p} = a_{n,p} * \exp(\frac{-b_{n,p}}{E})$$

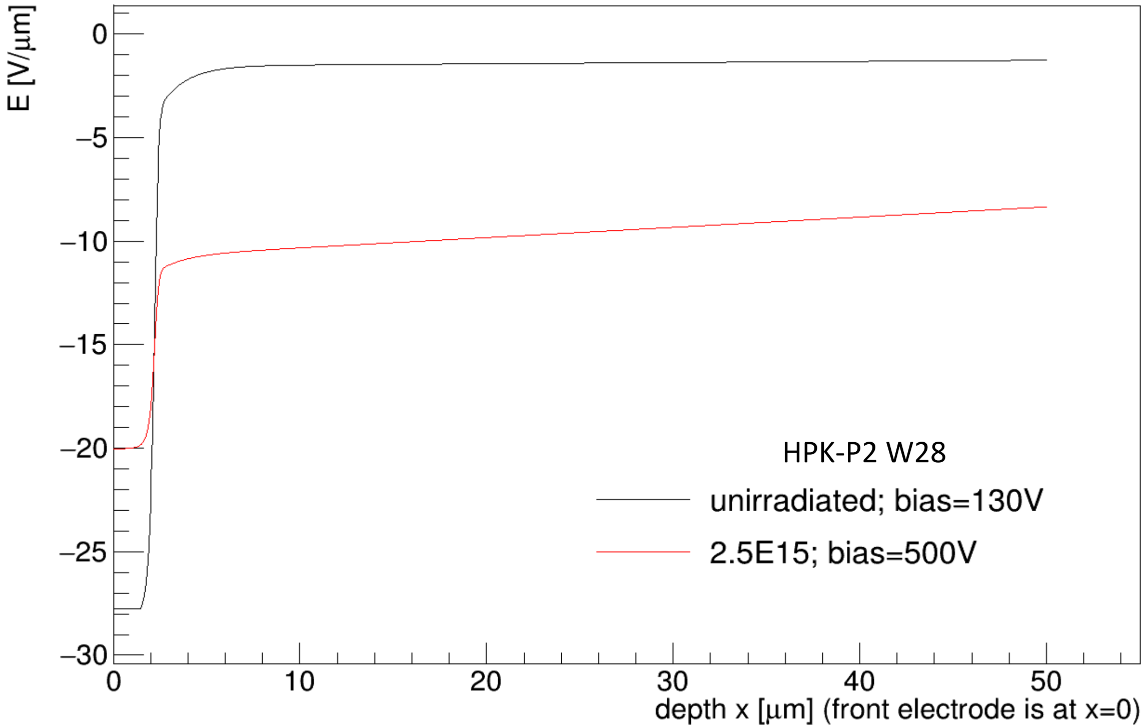
$a = prefactor$
$b = critical\ field$
$E = electric\ field$

- *a* and *b* are the parameters that need to be determined
- Since fields in LGADs are rarely >35 V/µm, impact ionization of holes is magnitude smaller than electrons -> can be excluded
  - a_p and b_p set to zero



Electric Field

- Simulate detector with KDetSim (kdetsim.org)
  - Detector Simulation Package
- User defines doping profile of the sensor -> KDetSim calculates the electric field

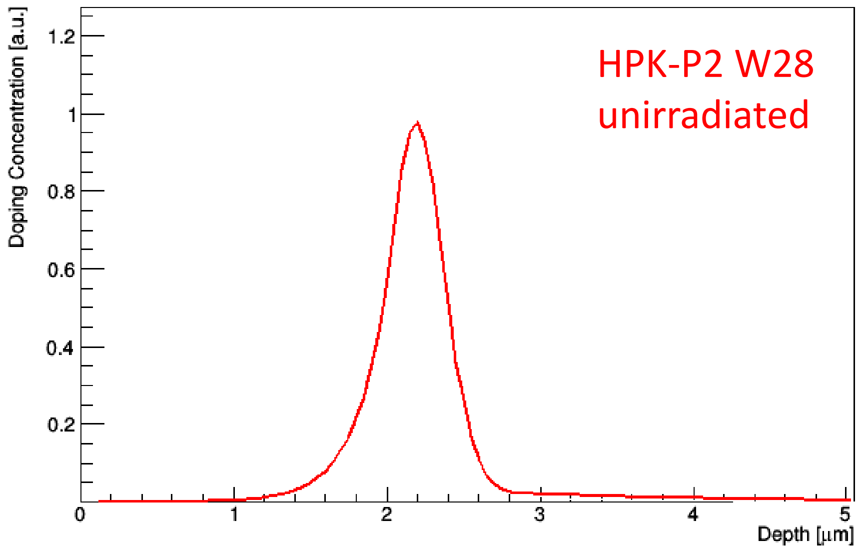


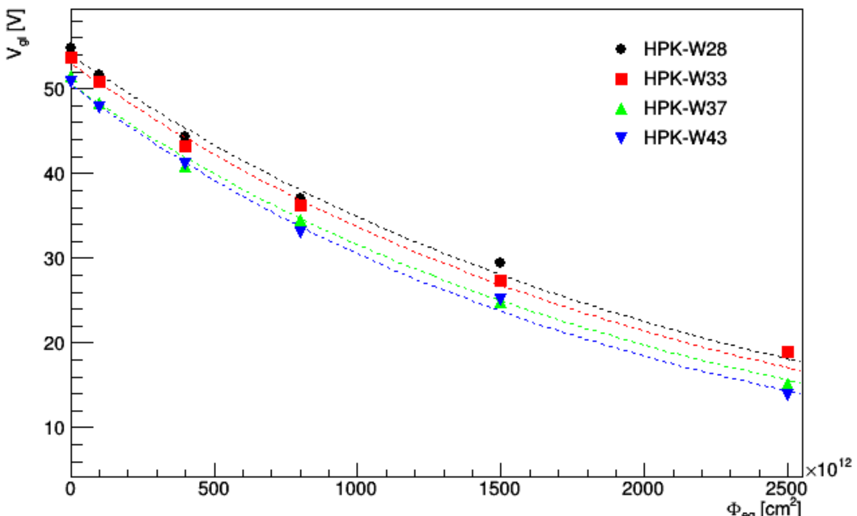
Doping Profile

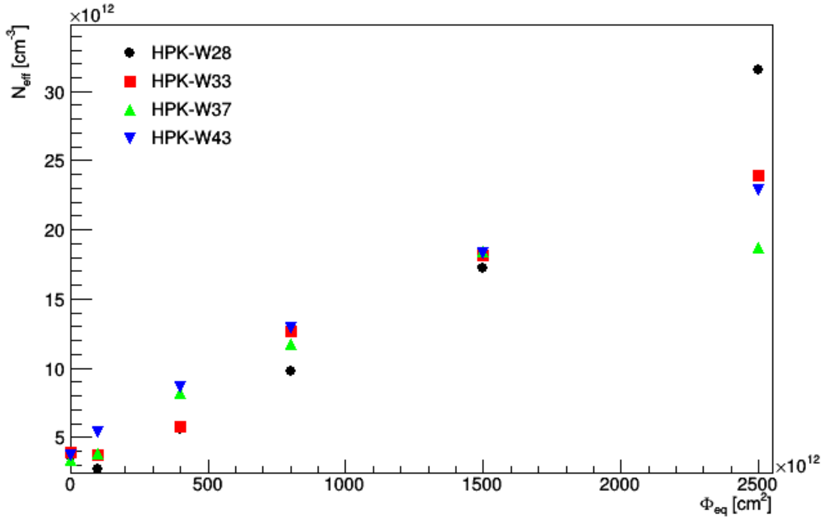
- Gain layer doping profiles for unirradiated sensors were provided by BNL
  - Absolute values not shown due to NDA
  - Only difference between profile of each wafer is peak concentration – shape remains the same
- For irradiated sensors
  - shape was assumed to remain unchanged
  - assumed amplitude decreases with ratio of $^{V_{gl}(\Phi)}/_{V_{gl}(0)}$
- Doping concentration in bulk:

$$N_{eff} = \frac{2\varepsilon_{Si}\varepsilon_0(V_{fd} - V_{gl})}{e_0(D - x_{gl})^2}$$

$\varepsilon_{Si,0}$ = permittivity of silicon/vacuum
e_0 = elementary charge
D = sensor thickness
x_{gl} = gain layer thickness







Gain

- Calculated analytically
- Multiplication coefficient: total number of e-h pairs created by single carrier generated at distance x

$$M(x) = \frac{\exp[\int_0^x (\alpha_n - \alpha_p) dx]}{1 - \int_x^W \alpha_p \exp[\int_0^x (\alpha_n - \alpha_p) dx]\, dx}$$

- Gain:

$$G = \frac{Q_{total}}{Q_{gen}} = \frac{\int_0^D e_0 \rho(x) M(x) dx}{\int_0^D e_0 \rho(x) dx}$$

$$\rho(x) = \mathit{ionization\ density}$$

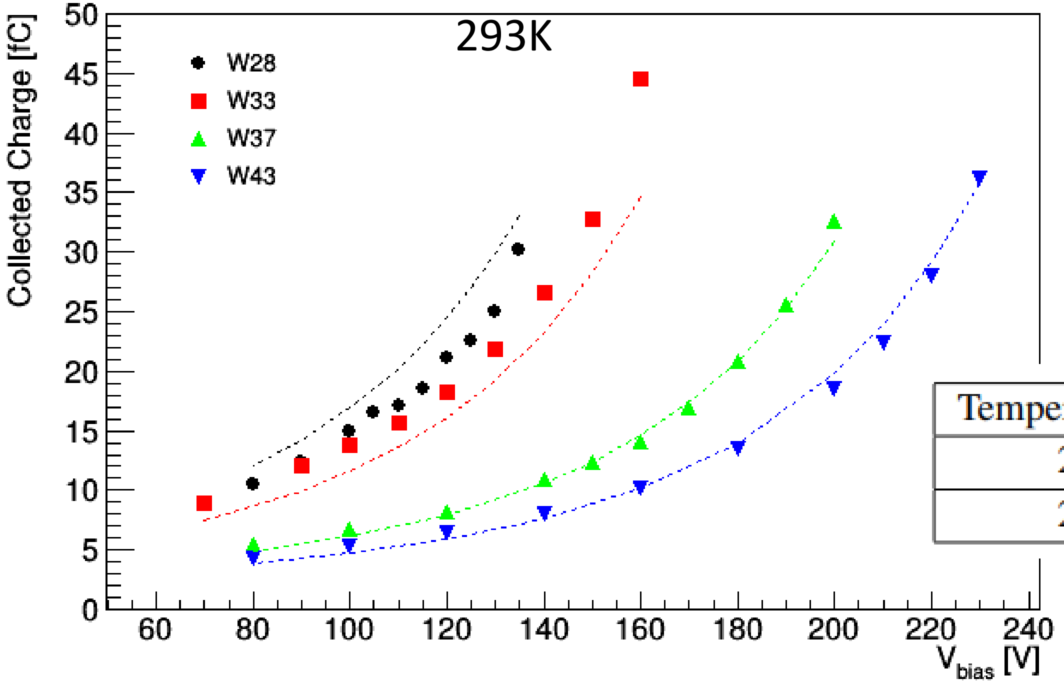
- To convert between Gain and Collected Charge: 1 G ≈ 0.6 fC

Minimization

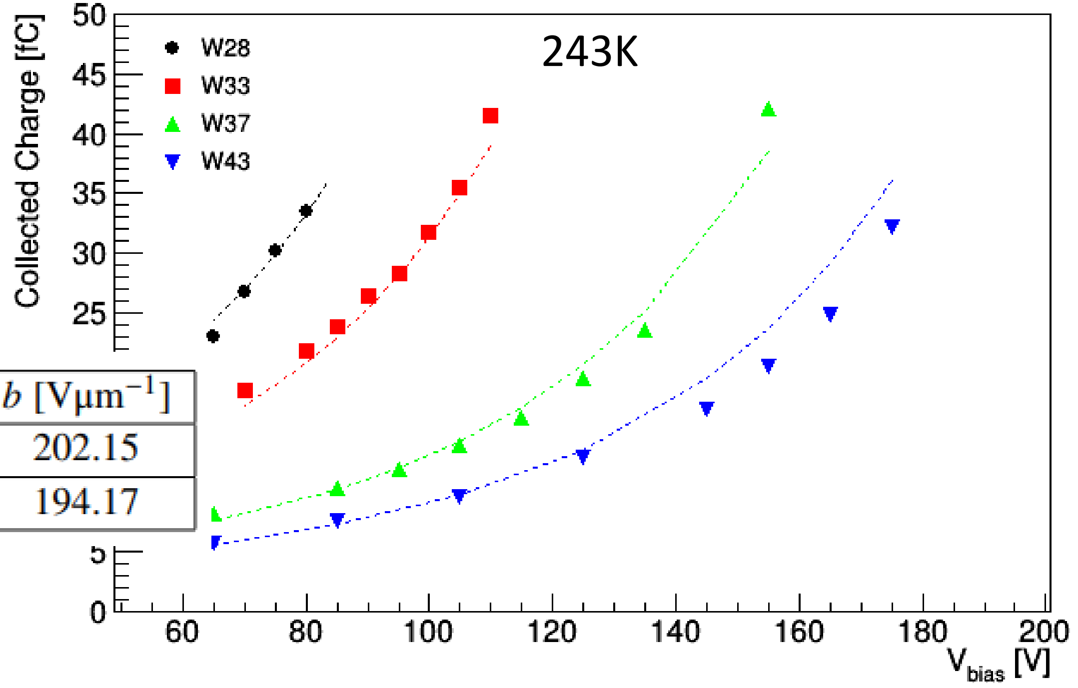
- Minimization estimator: $$\chi^2 = \left(\sum_{all\ voltages} (G_{sim} - G_{meas})^2\right)/N$$

$G_{sim,meas} = simulated/measured\ gain$
$N = no.\ voltage\ points$

- All wafers, unirradiated, at two temperatures used in minimization -> so we can determine temperature dependence



Temperature [K]	a [μm^{-1}]	b [Vμm^{-1}]
293	2990.0	202.15
243	3000.7	194.17

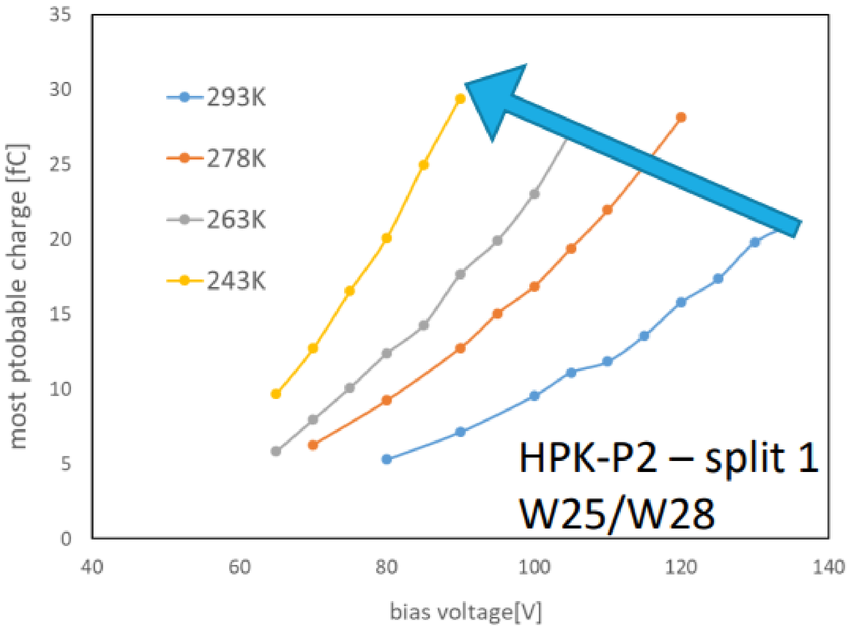


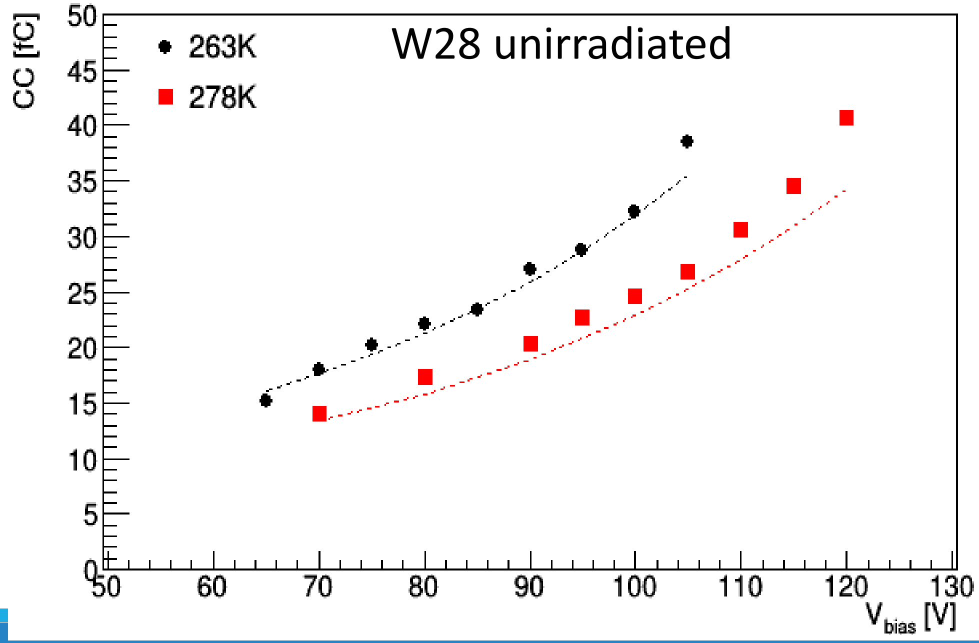
Temperature Dependence

- Gain, hence impact ionisation, appears to be a strong function of temperature.
- Assumed linear temperature dependence:

$$a = a_0 + k_a * T\ ;\ b = b_0 + k_b * T$$

- a_0=3053 µm^{-1}; k_a=-0.215 µm^{-1}K^{-1}; b_0=155.4 Vµm^{-1}; k_b=0.160 V µm^{-1}K^{-1}
- To test, calculated CC for unirradiated W28 at 263 K & 278 K
  - Linear dependence gives reasonable agreement

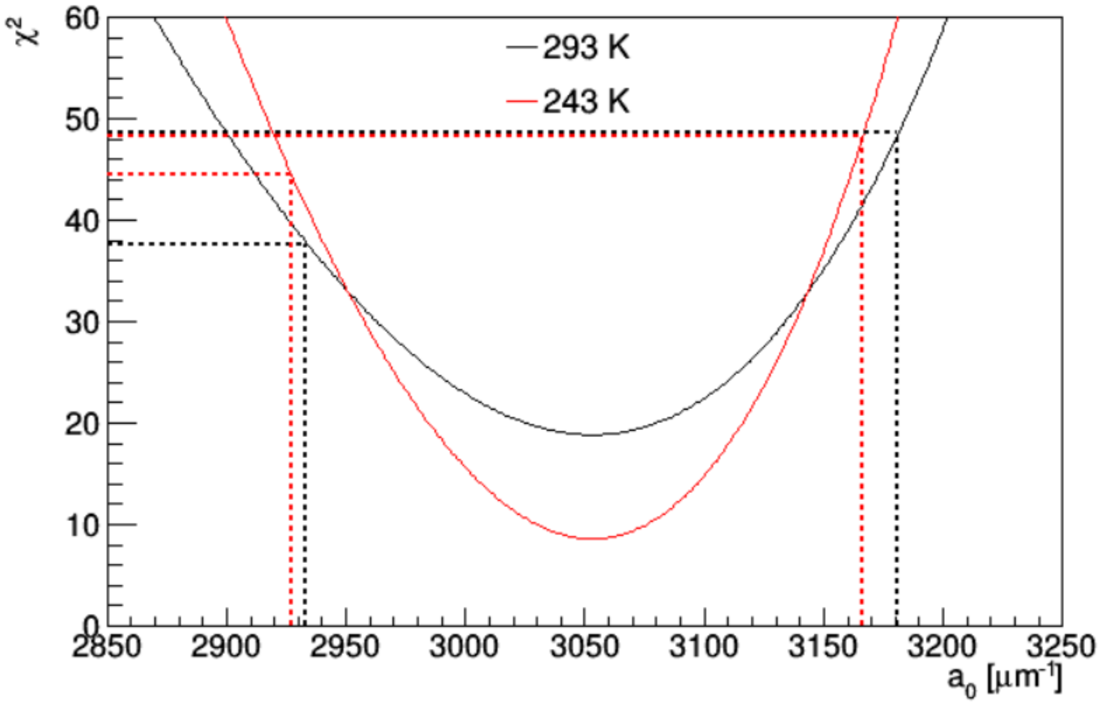




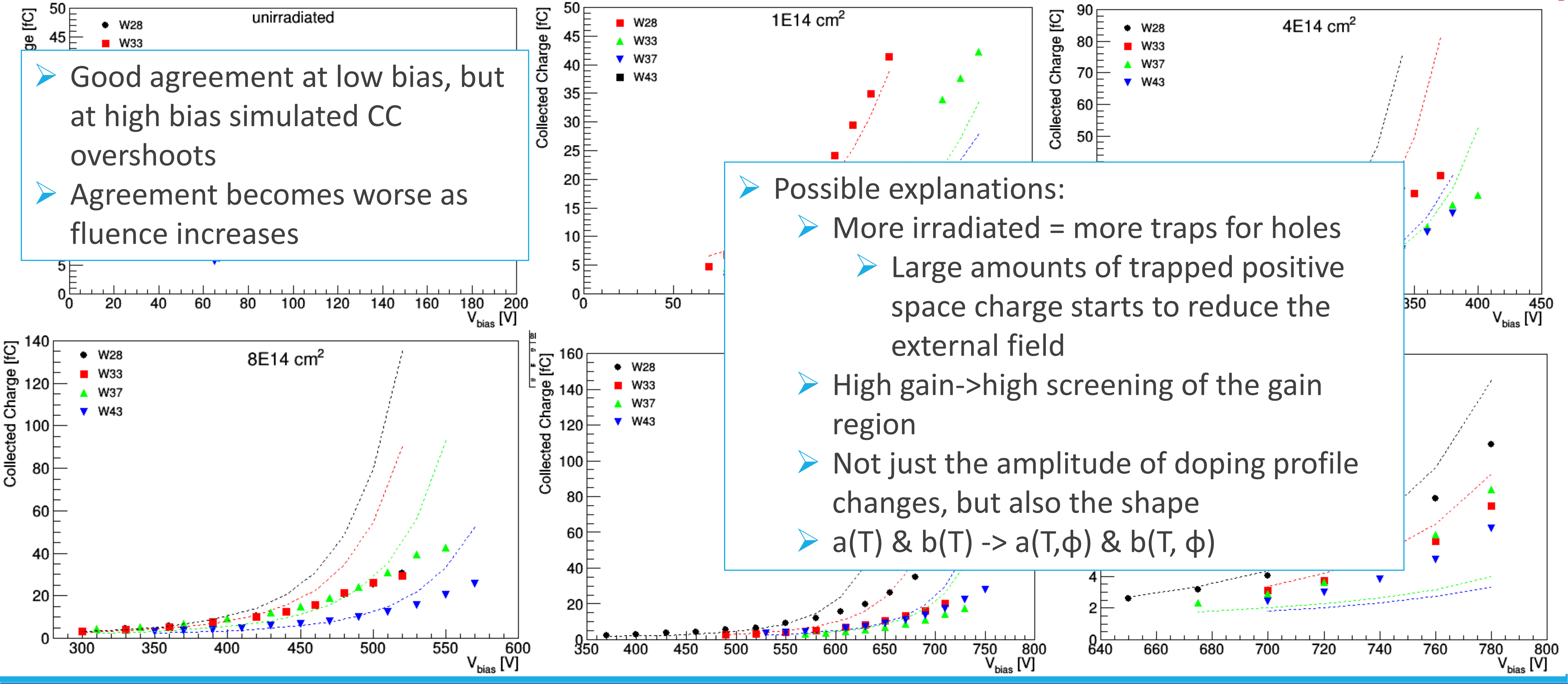
Uncertainty on parameters

- Uncertainty on measured collected charge, Q_{meas} is ±15%
- Use χ^2 to estimate uncertainty
  - Calculate χ^2 at upper and lower limit of Q_{meas} (for both temperatures to double check)
  - Find values of a_0 that correspond to upper and lower χ^2 (keeping other three parameters same)
  - Repeat for other three parameters
- Uncertainties:
  - a_0 ±120 μm^{-1}
  - k_a ±0.45 $\mu m^{-1}K^{-1}$
  - b_0 ±1.1 V μm^{-1}
  - k_b ±0.004 V $\mu m^{-1}K^{-1}$

	χ^2		
Temperature [K]	Q_{meas}	$Q_{meas} - 15\%$	$Q_{meas} + 15\%$
293	18.9	37.6	48.6
243	8.6	44.5	48.2



Testing on irradiated sensors



- Good agreement at low bias, but at high bias simulated CC overshoots
- Agreement becomes worse as fluence increases

- Possible explanations:
  - More irradiated = more traps for holes
    - Large amounts of trapped positive space charge starts to reduce the external field
  - High gain->high screening of the gain region
  - Not just the amplitude of doping profile changes, but also the shape
  - a(T) & b(T) -> a(T,ϕ) & b(T, ϕ)

Summary

- Proposed model for impact ionization of electrons in LGADs uses Chynoweth's model and the following parameters

$$\alpha = a * \exp(-b/E)$$

$$a = (3053 \pm 120) - (0.215 \pm 0.45) * T$$
$$b = (-155.4 \pm 1.1) + (0.160 \pm 0.004) * T$$

- Temperature dependence was shown to be valid on unirradiated sensors
- Testing on irradiated sensors showed that further work should be done to develop a model for irradiated sensors:
  - Does doping profile shape/concentration change with irradiation?
  - Are the parameters also dependent on fluence?
- This model was only tested on HPK-P2 sensors -> needs to be tested on sensors from different producers and runs