Impact Ionisation Parameters for LGADs

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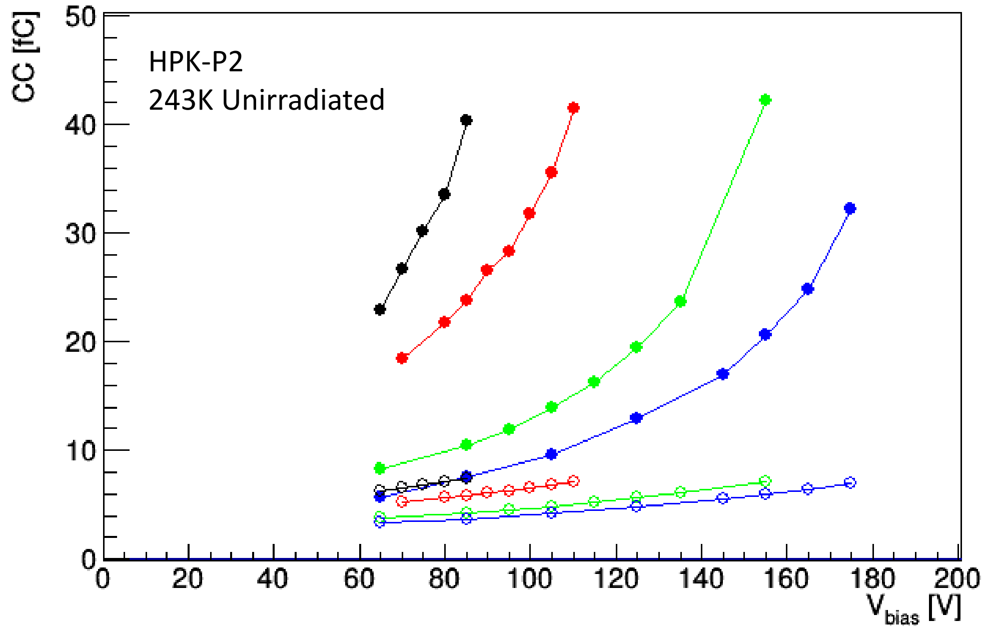
MANY THANKS TO IHEP COLLEAGUES FOR DOPING PROFILES

39TH RD50 WORKSHOP, VALENCIA, SPAIN

Motivation

- Previous determinations of impact ionisation parameters for silicon do not give correct value of collected charge for LGADs
  - Obtained on different devices via different methods
  - See right plot as example: collected charge (CC) calculated from parameters from Kohdin et al give too low value for LGAD
- Some used laser carrier injection (e.g. Van Overstraeten[2], Massey[3])
  - Larger charge density leads to screening of external field -> reduced gain [see E. Currás talk at 38th RD50 workshop]
  - We use electron (~mip) from Sr^{90} source in timing setup [see G. Kramberger's talk at 37th RD50 workshop for setup details]
  - Mip produces larger charge density than laser which changes the effective impact ionisation
- We need new model that is more applicable to LGADs and gives better agreement for our measurements
- All results shown in this talk are preliminary

Closed markers: measured CC
Open markers: calculated CC using Kohdin's model [1]



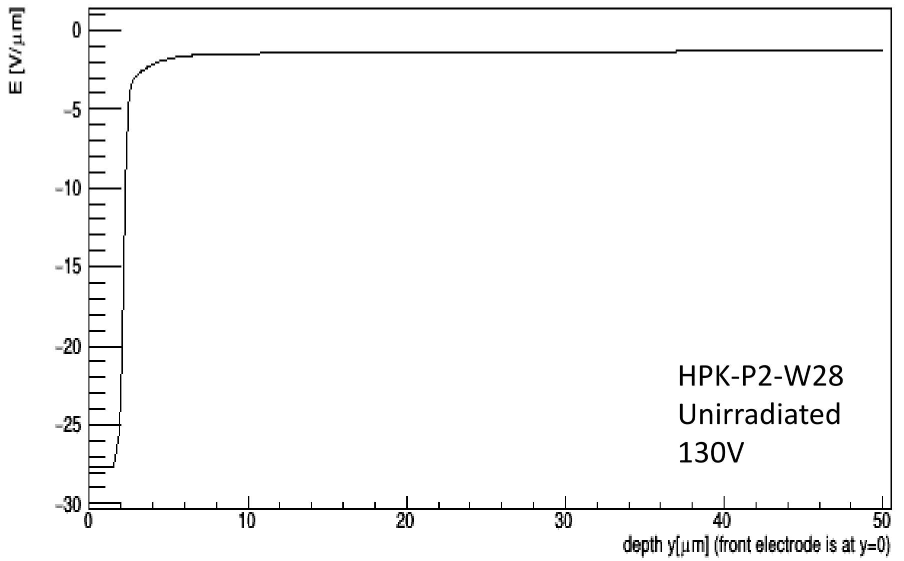
[1]Khodin, Alexandre et al. "Silicon avalanche photodiodes for particle detector:: modelling and fabrication." *Nucl. Instrum. Meth. A, vol.* 465, 2001

[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.

Calculation of Gain & Collected Charge

- Calculate detector field with KDetSim package (kdetsim.org)
  - Electric field determined from doping profile for particular bias



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

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

Impact ionisation coefficients, $\alpha_{n,p}$: no. e-h pairs created per unit distance travelled by an electron/hole

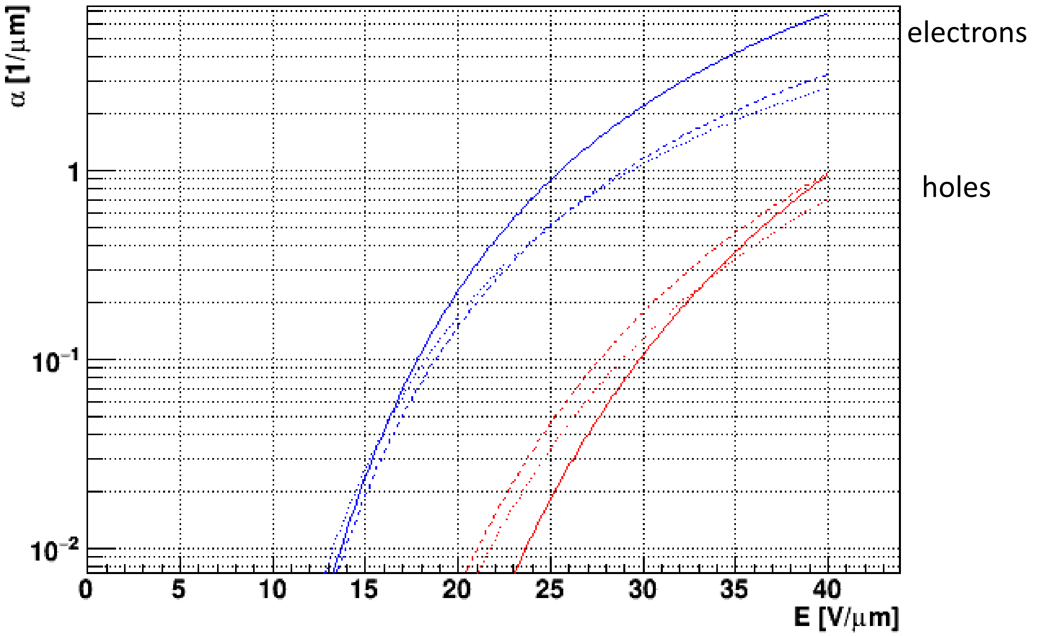
- Chynoweth law: $\alpha_{n,p} = a_{n,p} * \exp\left({}^{-b_{n,p}}/_{E}\right)$; $E = Electric\ field$

- Gain: $G = \frac{Q_{total}}{Q_{gen}} = \frac{\int_0^D e_0\rho(x)M(x)dx}{\int_0^D e_0\rho(x)dx}$; ρ(x)=e-h density

- Collected charge is calculated for each bias (1 G ≈ 0.5 fC)

Parameters a & b

- Chynoweth law: $\alpha_{n,p} = a_{n,p} * \exp\left(^{-b_{n,p}}/_{E}\right)$; $E = Electric\ field$
- Set a_p & b_p to zero
  - Large enough difference in impact ionisation coefficients between electrons and holes allows for operation in conditions that allow for electron multiplication but not hole multiplication
  - Only electron multiplication is taken into account; hole multiplication is excluded

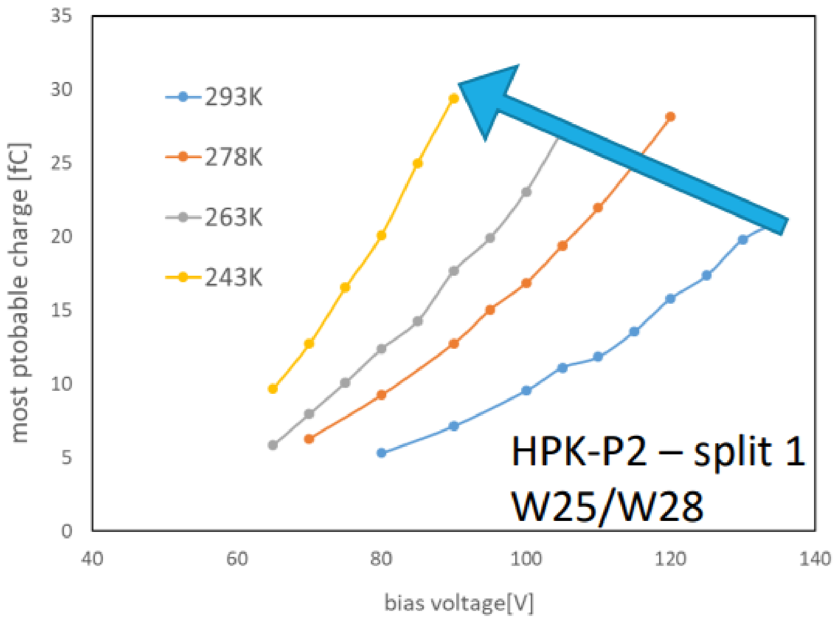


Parameters a & b dependencies

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

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

- Future work: add a dependence on fluence E.g. $a_0(\phi)=c+d*\phi$
  - Why: irradiation introduces impurities



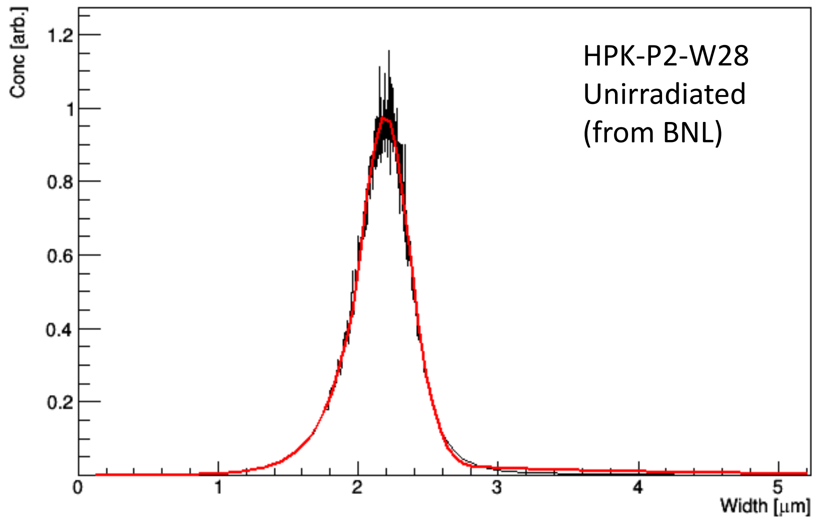
Doping Profile

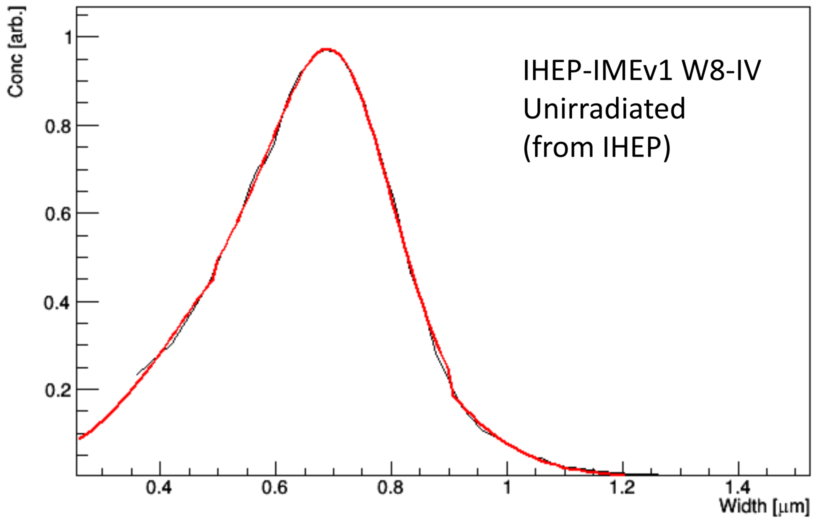
- Determine best fit for doping profile in gain layer(shown right):
  - HPK-P2 W28 (doping profile from BNL)
  - NDLv3 (doping profile from IHEP)
  - IHEP-IMEv1 (doping profile from IHEP)
- Doping concentration in bulk determined from CV measurements

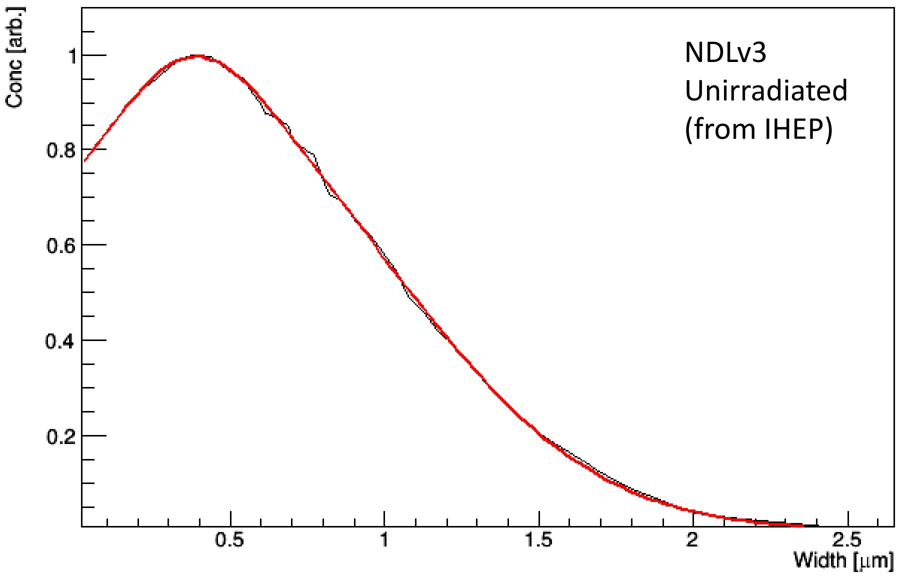
$$N_{eff} = \frac{2\varepsilon_{si}\varepsilon_0\left(V_{fd} - V_{gl}\right)}{e_0\left(D - x_{gl}\right)^2}$$

D=Sensor thickness

x_{gl}=gain layer thickness



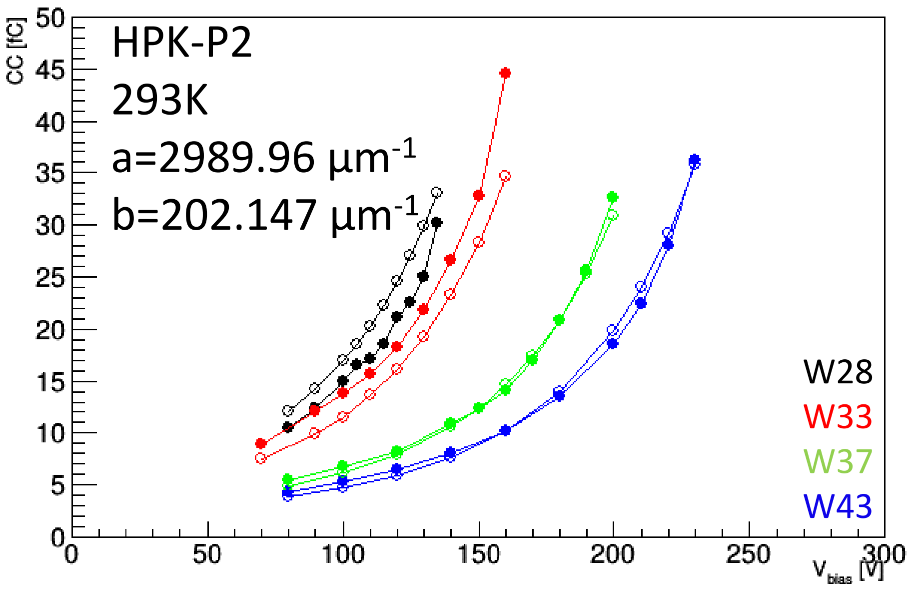


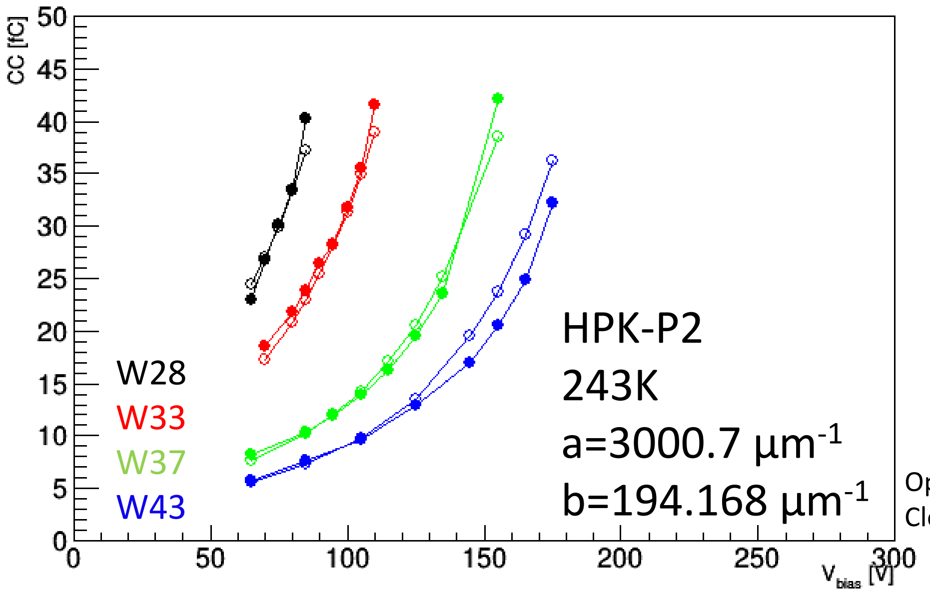


Thanks to Mei Zhao (IHEP) for NDL & IHEP-IME doping profiles!

Determining parameters

- Used HPK-P2 un-irradiated sensor measurements to determine the parameters
  - HPK-P2 is well measured
- Used charge collection(CC) measurements for wafers 28, 33, 37 and 43 at 293K & 243K
  - Two temperatures allow for determination of temperature dependence
  - Estimator for minimisation $\chi=\sum_{all\ voltages}(G_{calc.} - G_{meas})^2$



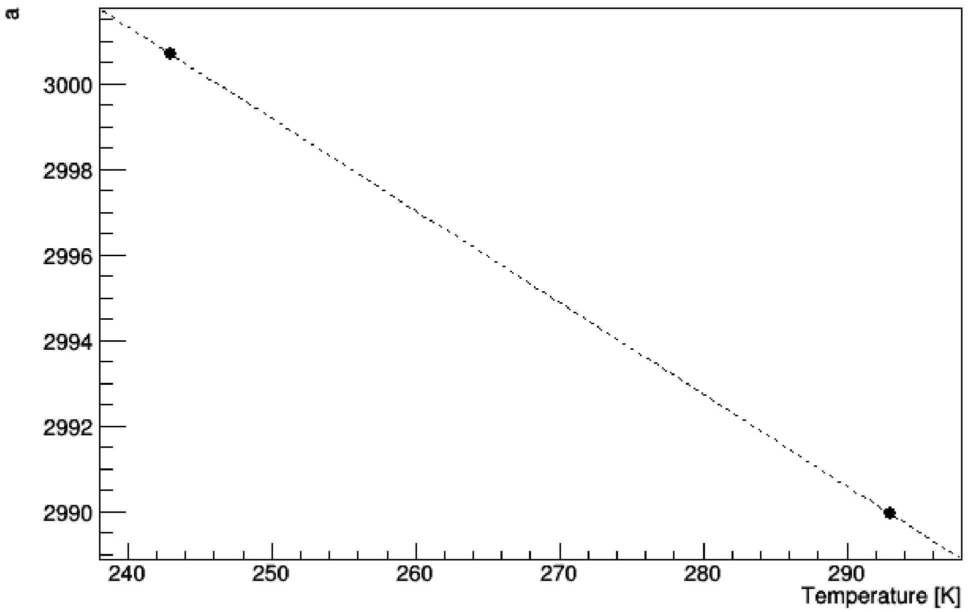


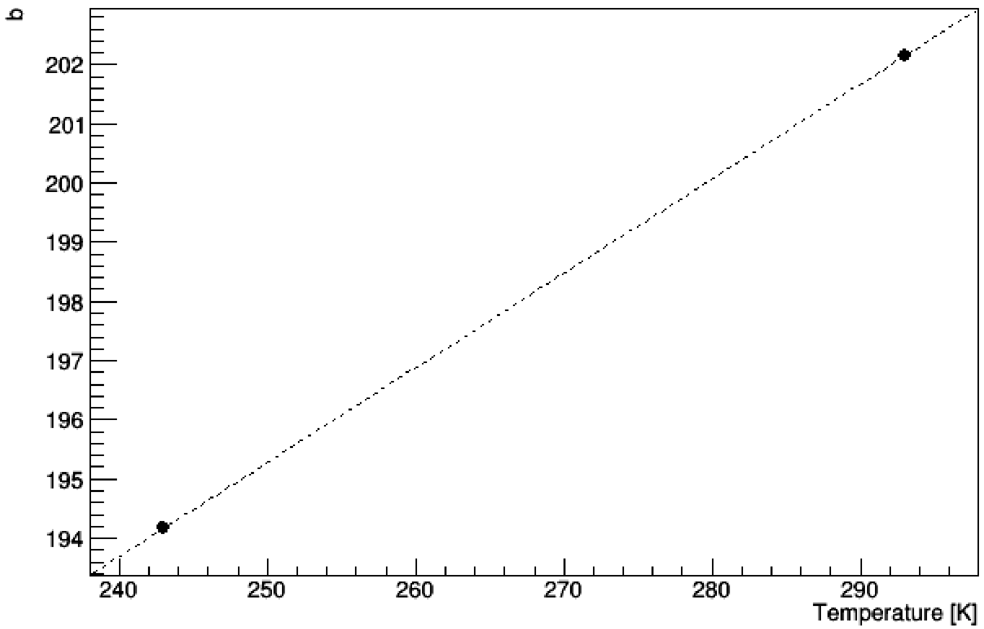
Open markers: fit
Closed markers: measured

Temperature dependence

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

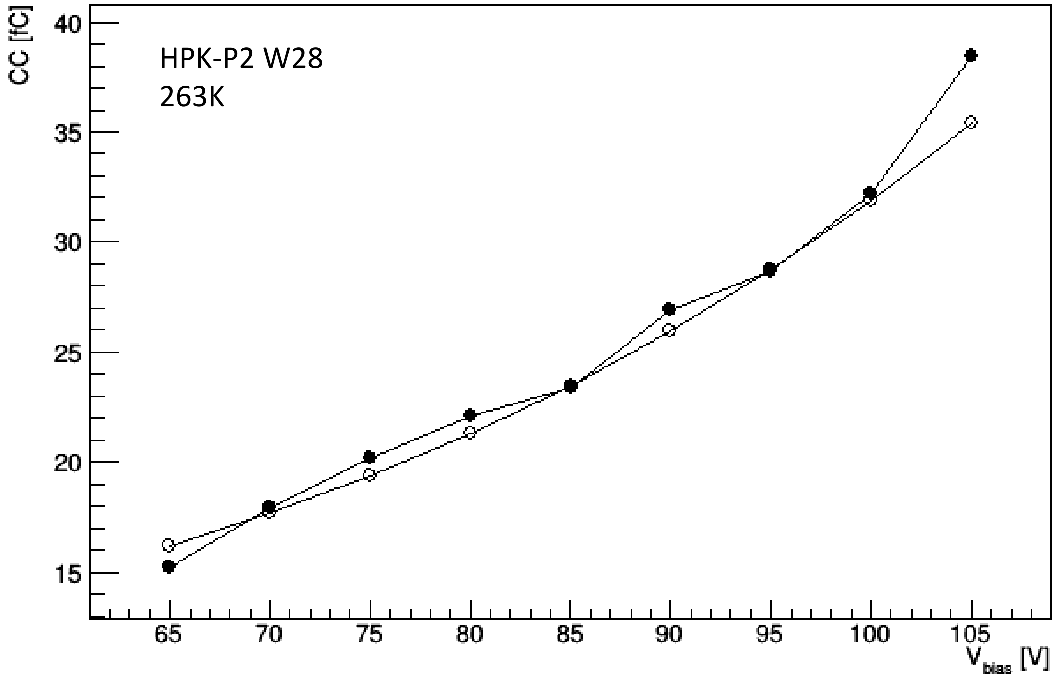
a_0=3.053e3 μm^{-1}; k_a=-0.215 μm^{-1}K^{-1}
b_0=1.554e2 μm^{-1}; k_b=0.160 μm^{-1}K^{-1}

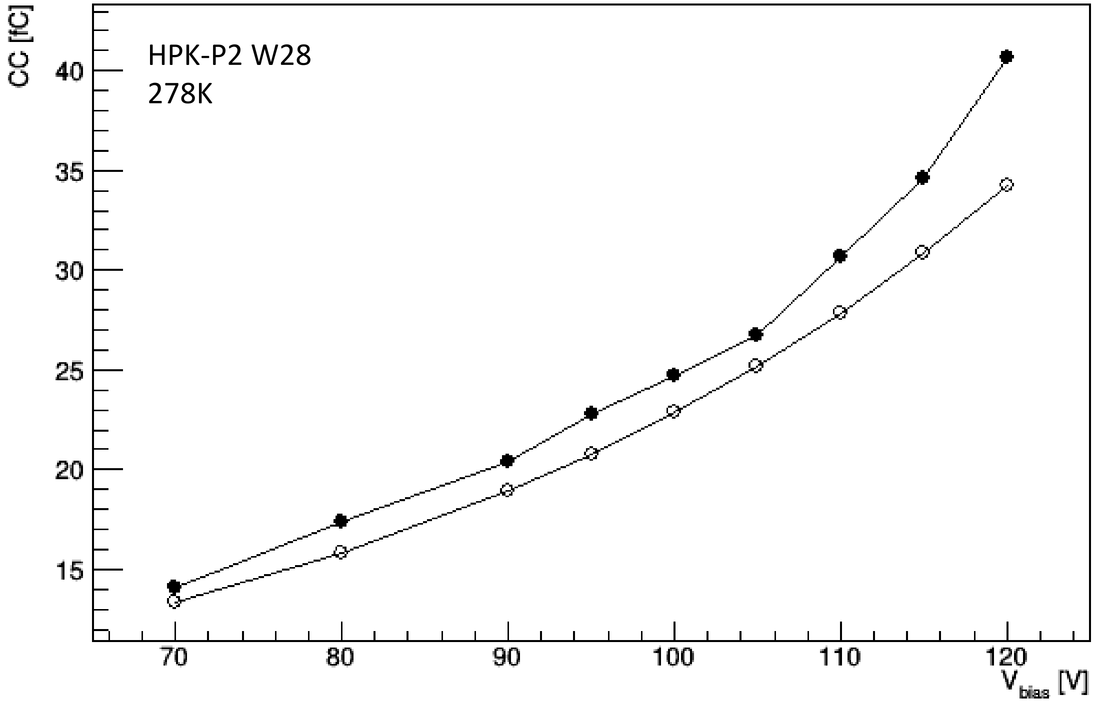




Testing the Temperature Dependence

- Parameters determined from 293K & 243K measurements
- Calculated the CC for the same HPK-P2 W28 sensor at 263K & 278K
  - Good agreement



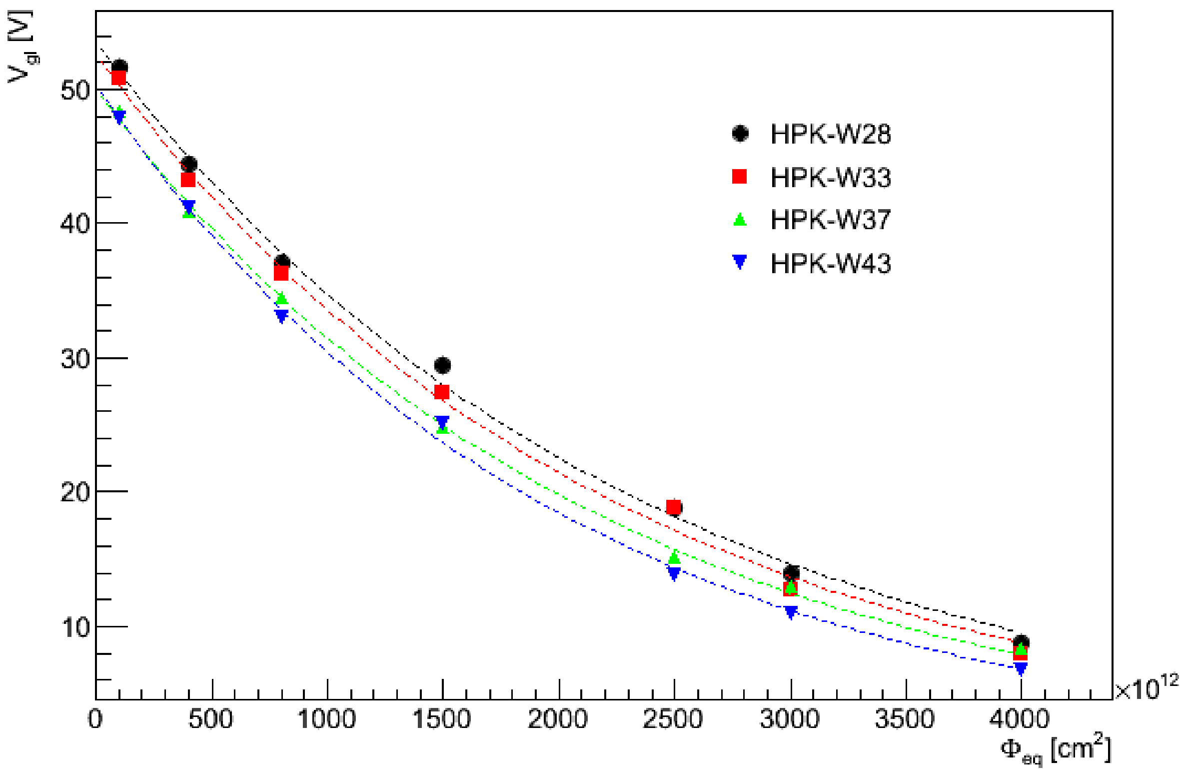


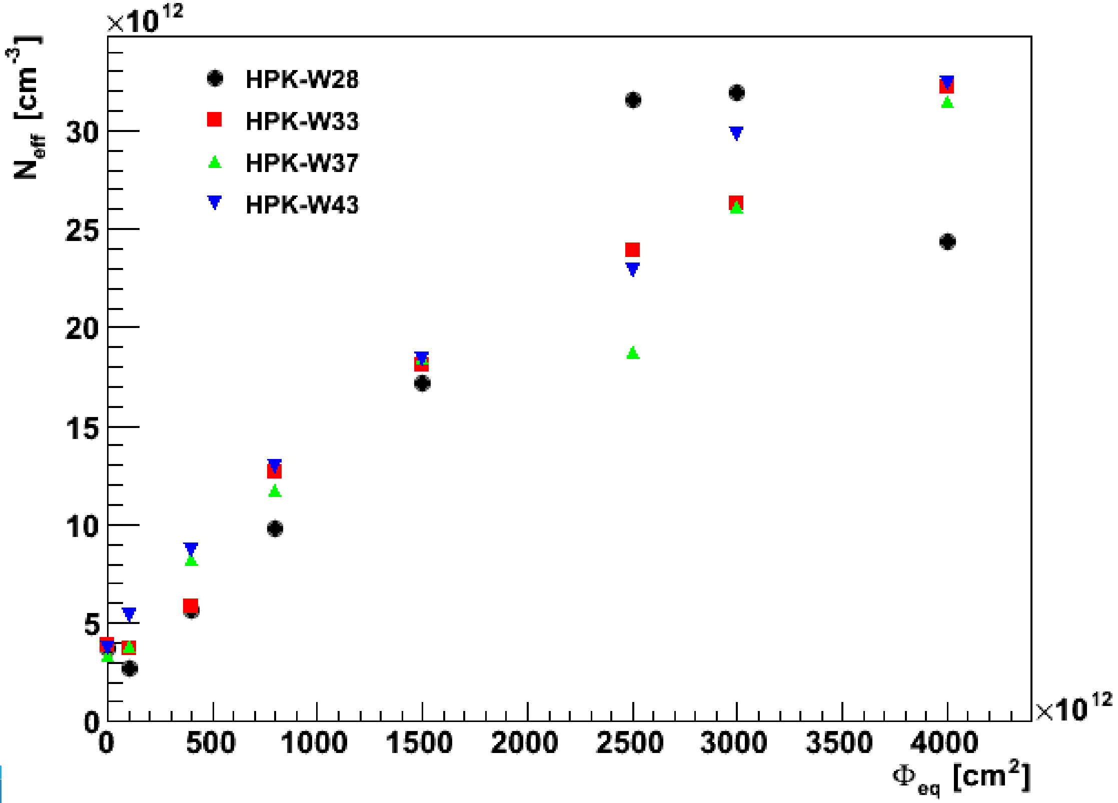
Open markers: calculated
Closed markers: measured

Irradiations

- HPK-P2 sensors irradiation with neutrons (JSI's Triga reactor) up to 2.5E15 cm^{-2}
- Used same gain layer doping profile as un-irradiated sensor, but decreased amplitude by $V_{gl}(\phi)/V_{gl}(0)$
- Bulk doping concentration was calculated at each fluence

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





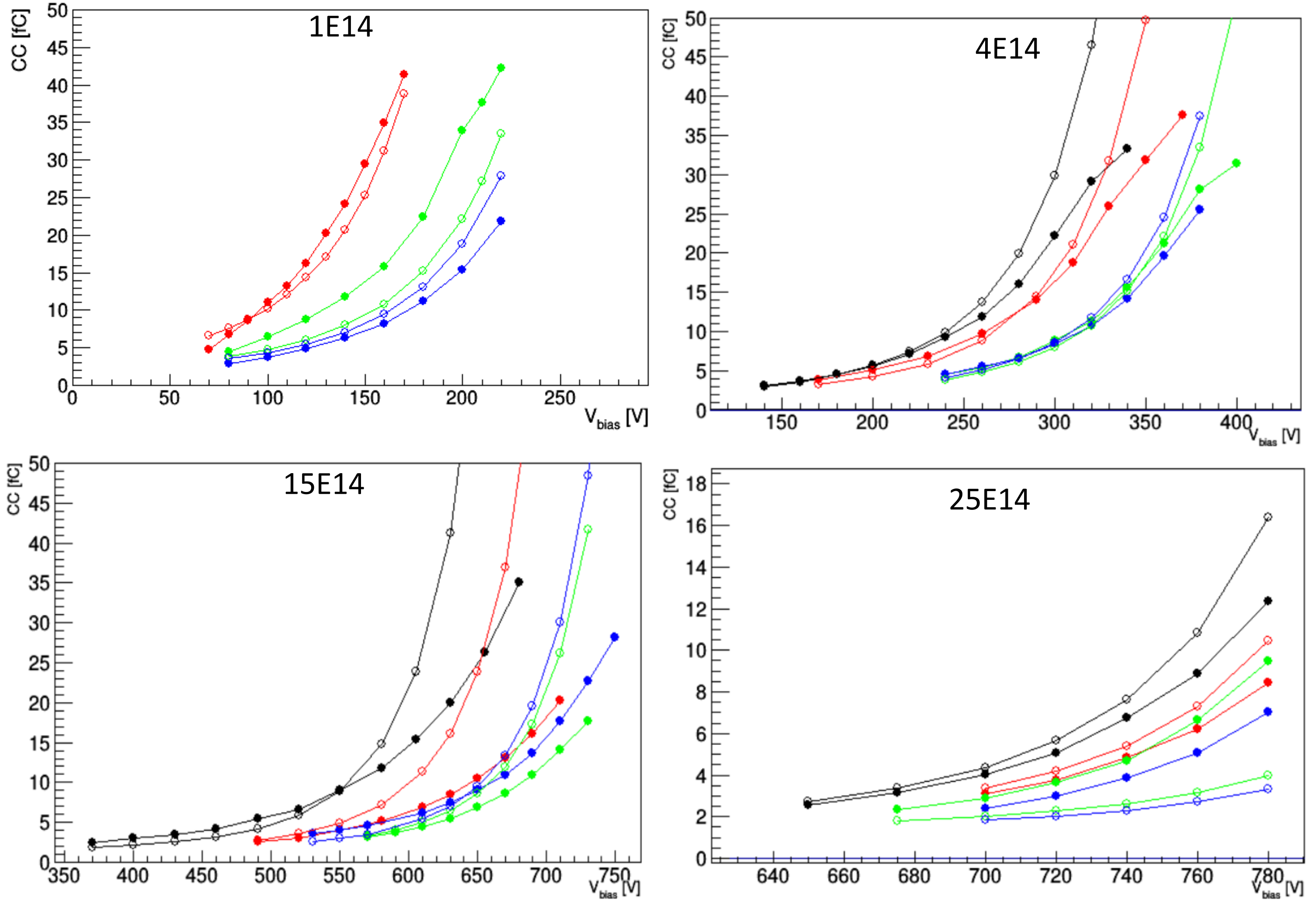
Testing across fluence range

JSI Ljubljana Slovenia

Slovenian Research Agency

HPK-P2

Open markers: calculated
Closed markers: measured

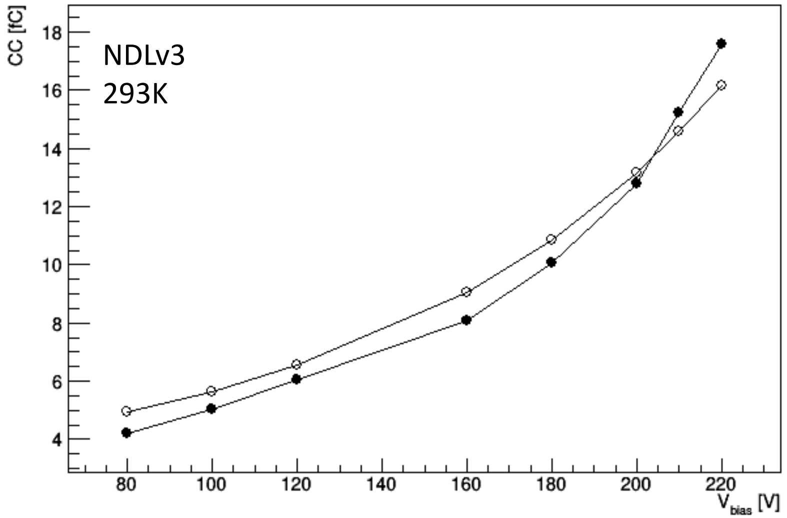


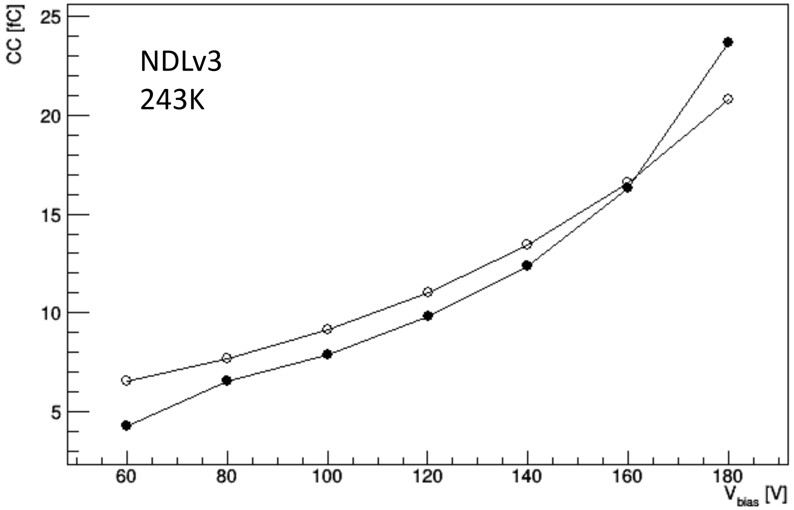
W28
W33
W37
W43

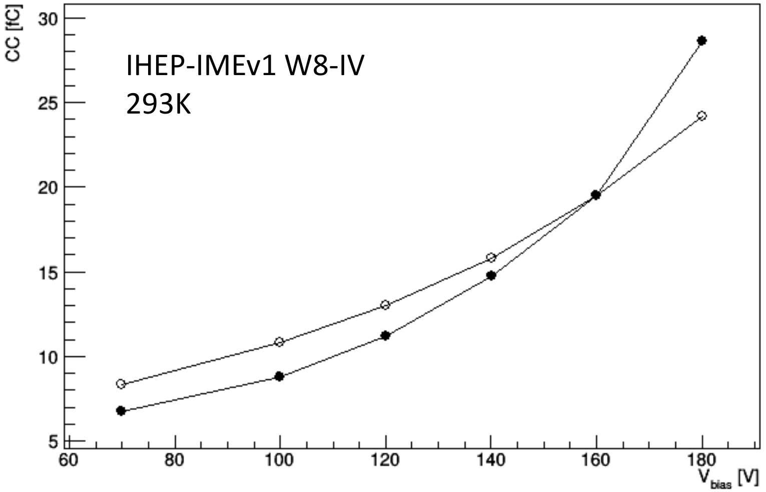
- Good agreement at low bias, but at high bias it overshoots.
- Possible explanations:
  - More irradiated = more traps for holes
    - Large amounts of trapped positive space charge starts to reduce the external field
  - It isn't just the amplitude of the doping profile that changes, but also the shape

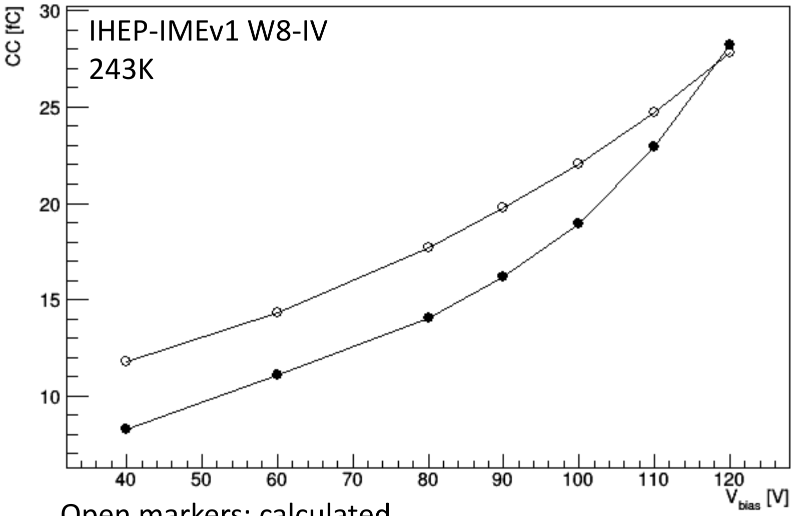
Testing across different producers

- Test on sensors by other producers:
  - Calculated CC for runs NDLv3 & IHEP-IMEv1 at 293K & 243K
  - All show good agreement between simulated and measured values
  - Again agrees with linear temperature dependence
- Note: Depth of profile was shifted for NDL & IHEP-IME to obtain this good agreement
  - Initially justified with uncertainty in n++ implant depth









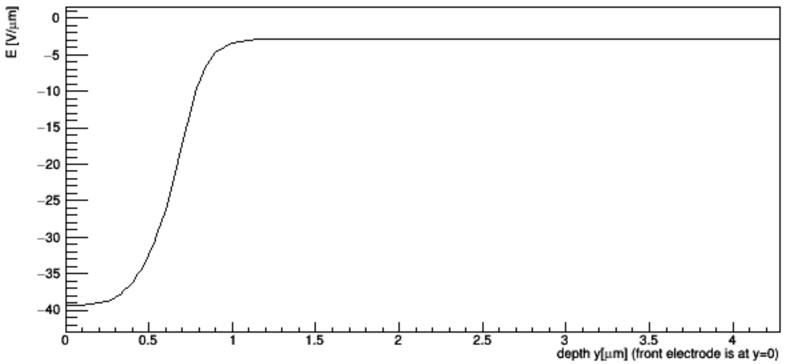
Open markers: calculated
Closed markers: measured

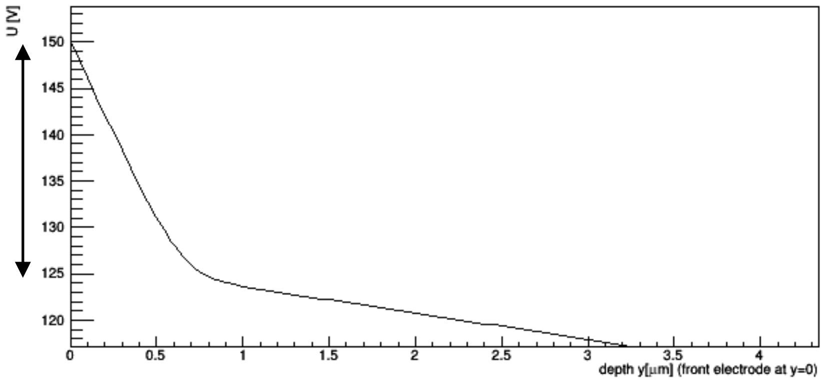
Shifting the doping profile

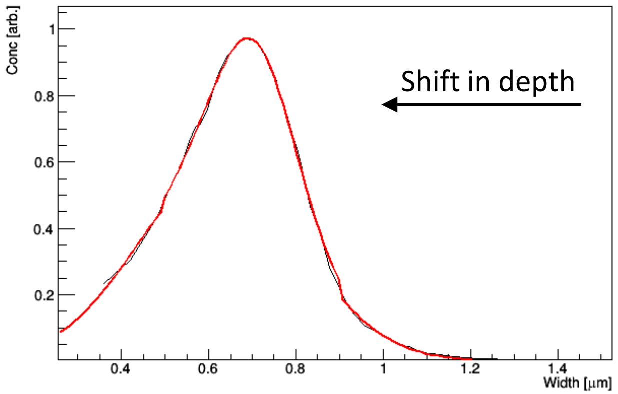
- Lots of uncertainties
  - Uncertainty in doping profile
  - Uncertainty in V_{gl} (+/- 0.5V)
- IHEP-IMEv1 W8-IV
  - (from CV measurements) Vgl=24 V

- Unshifted doping profile gives the correct value for V_{gl}
- The shifted doping profile gives incorrect value
  - Shift was x-0.22 µm. Since gain layer is now smaller, V_{gl} is also smaller
  - Problem to be solved: why does shifting profile give correct gain but incorrect V_{gl}?

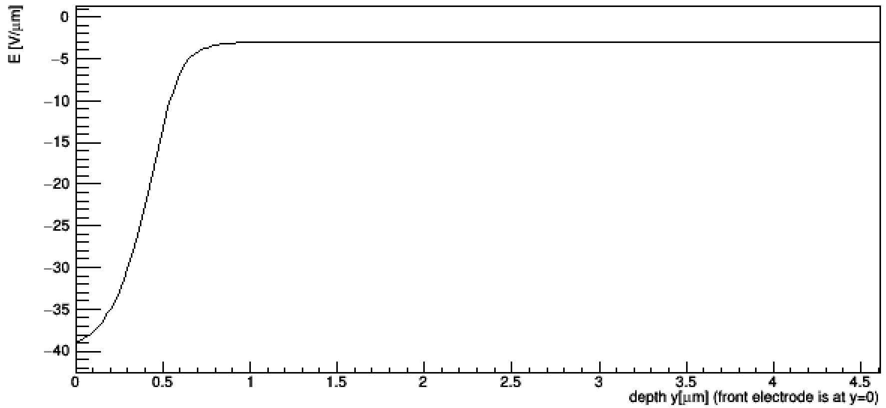
Unshifted

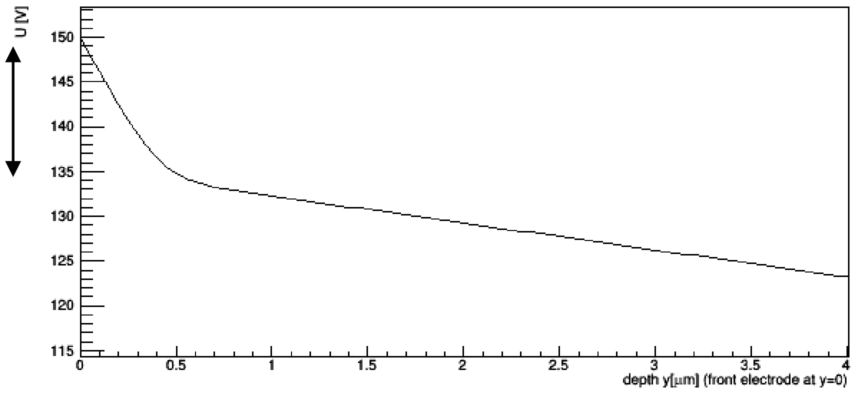






Shifted

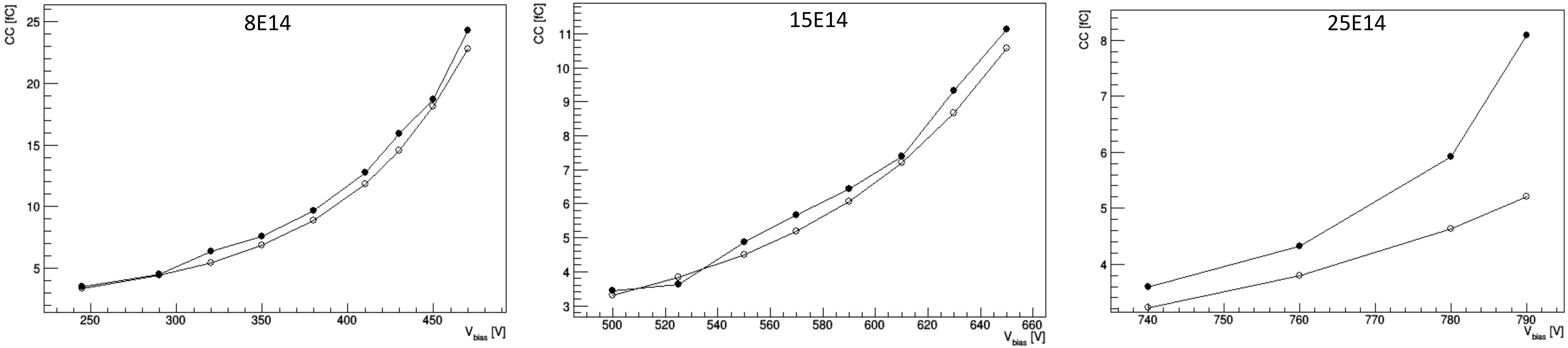




Testing across fluence range – IHEP-IME

- Fairly good agreement for lower fluences
- These were calculated using the exact same shift in the doping profile as for the unirradiated measurements

IHEP-IMEv1 W8-IV



Open markers: calculated
Closed markers: measured

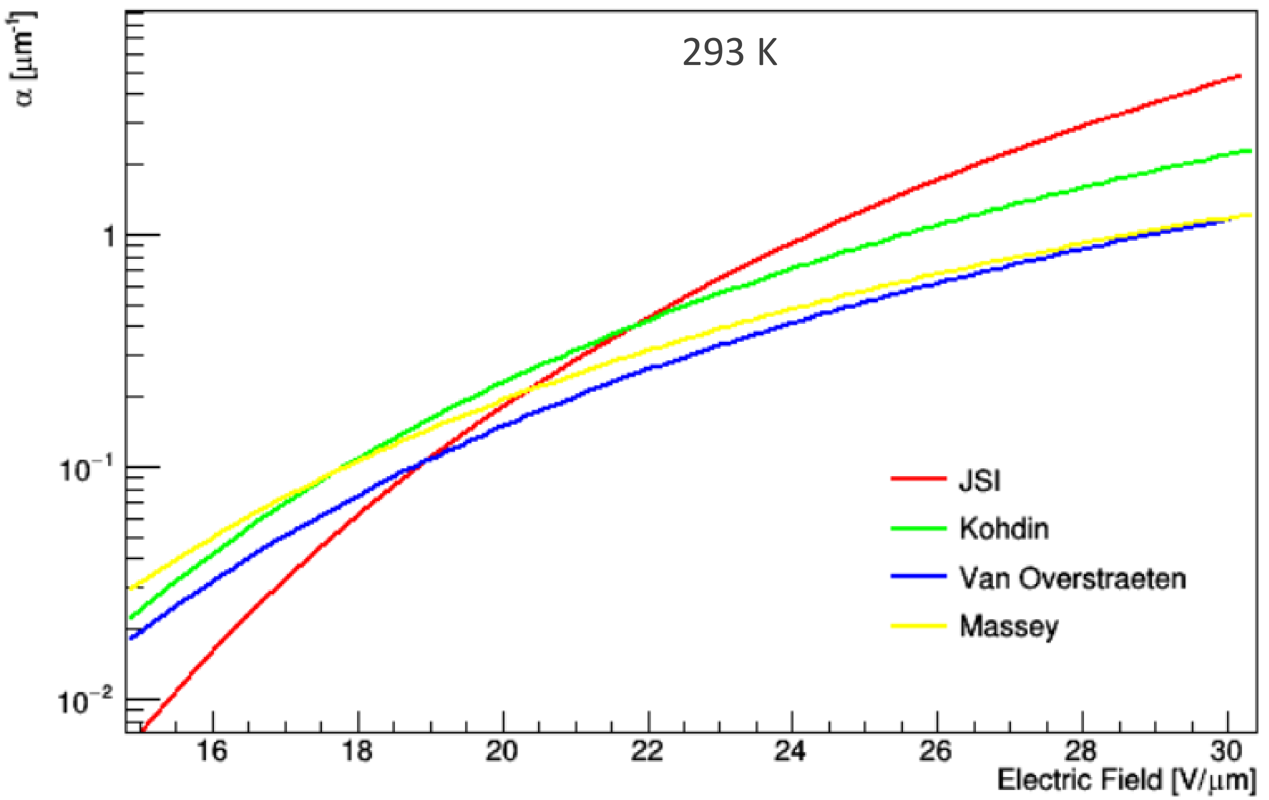
Comparison to previous models

- Overstraeten & Massey both use Chynoweth's law

$$\alpha_{n,p} = a_{n,p} * \exp\left({}^{-b_{n,p}}/_{E}\right)$$

293 K

	a [µm^{-1}]	b [µm^{-1}]
JSI	2989.96	202.147
Van Overstraeten	70.3	123.1
Massey	44.3	111.2



Kohdin uses McIntyre's approach: $\alpha_{n,p} = a_{n,p} * \exp(-b_{n,p}({}^{20}/_{E} - 1))$

a_n=0.23 µm^{-1} ; b_n=6.78 µm^{-1}

R. J. McIntyre, "A new look at impact ionization-Part I: A theory of gain, noise, breakdown probability, and frequency response," in *IEEE Transactions on Electron Devices*, vol. 46, no. 8, 1999

- Remember: Preliminary!

Summary

- Used CC measurements and simulations of HPK sensors to determine impact ionisation parameters for LGADs
- Observed linear dependence of parameters a & b on temperature
- Tested parameters by calculating CC for:
  - Same HPK sensors at different temperature – good agreement
  - sensors from other producers – once doping profile is shifted we get good agreement, including across temperatures
    - But this then impacts the simulated electric field and gives wrong V_{gl}
  - sensors irradiated to different fluences – starts to agree less at higher bias & irradiation
    - Add dependence on fluence? E.g. $a_0(\phi)=c+d*\phi$

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

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

a_0=3.053e3 μm^{-1}; k_a=-0.215 $\mu m^{-1}K^{-1}$
b_0=1.554e2 μm^{-1}; k_b=0.160 $\mu m^{-1}K^{-1}$

This work is preliminary: checks need to be done