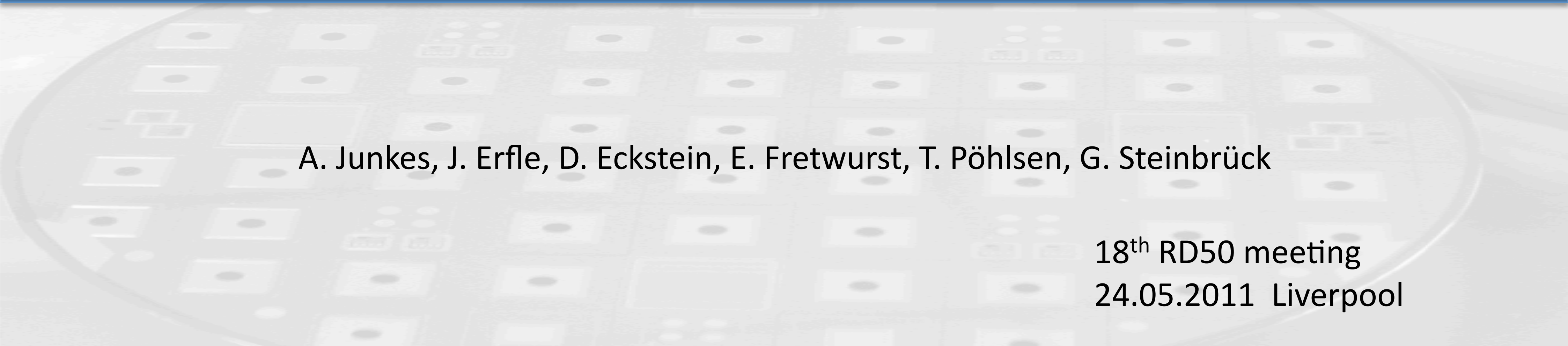
Influence of material defects on the electrical properties of test-diodes for future CMS tracking detectors



A. Junkes, J. Erfle, D. Eckstein, E. Fretwurst, T. Pöhlsen, G. Steinbrück

18th RD50 meeting
24.05.2011 Liverpool

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

CMS Germany
BMBF FSP-CMS

Test-sensors for future CMS tracking detectors

Pad diodes, strips, strixel, MOS.... In **n-type** und **p-type** (with ***P-spray*** and *P-stop*):

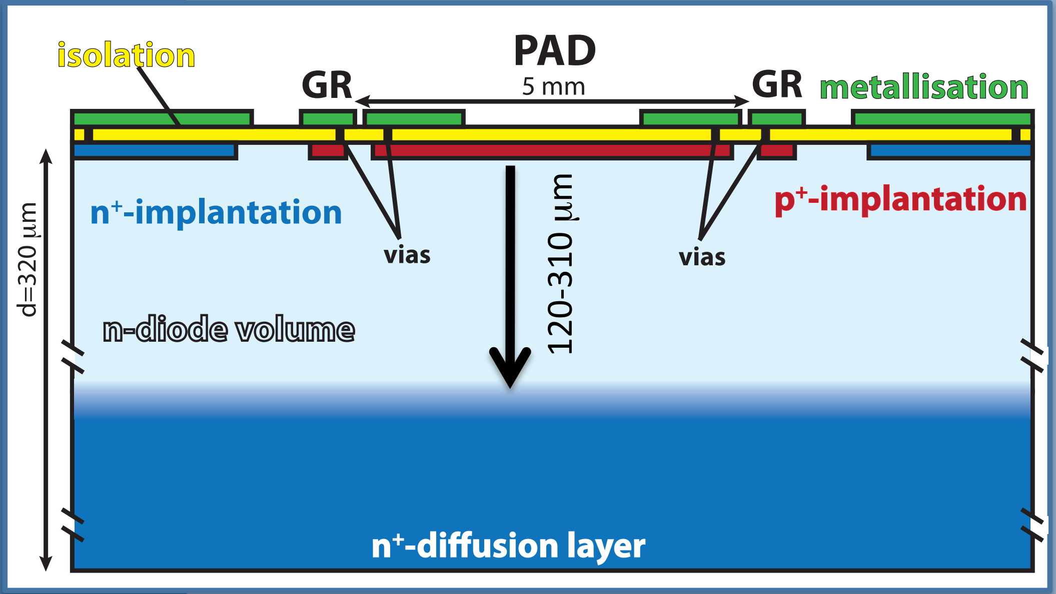
- **Float Zone (120 μm, 200 μm, 320 μm)**
- **Magnetic Czochralski (200 μm)**
- Epitaxically grown (50 μm, 70 μm, 100 μm)

Irradiation campaign:

- 1 MeV neutrons at TRIGA Reactor, Ljubljana
- 25 MeV protons at KIT, Karlsruhe

Measurements:

Capacitance-Voltage (C-V) & Current-Voltage Characteristics (I-V), Charge collection efficiency (CCE), Transient current technique (TCT), Si-Defektanalysen (DLTS, TSC)



Aim: Complete characterisation of available silicon materials and sensor designs

Test-sensors for future CMS tracking detectors

Pad diodes, strips, strixel, MOS.... In **n-type** und **p-type** (with ***P-spray*** and *P-stop*):

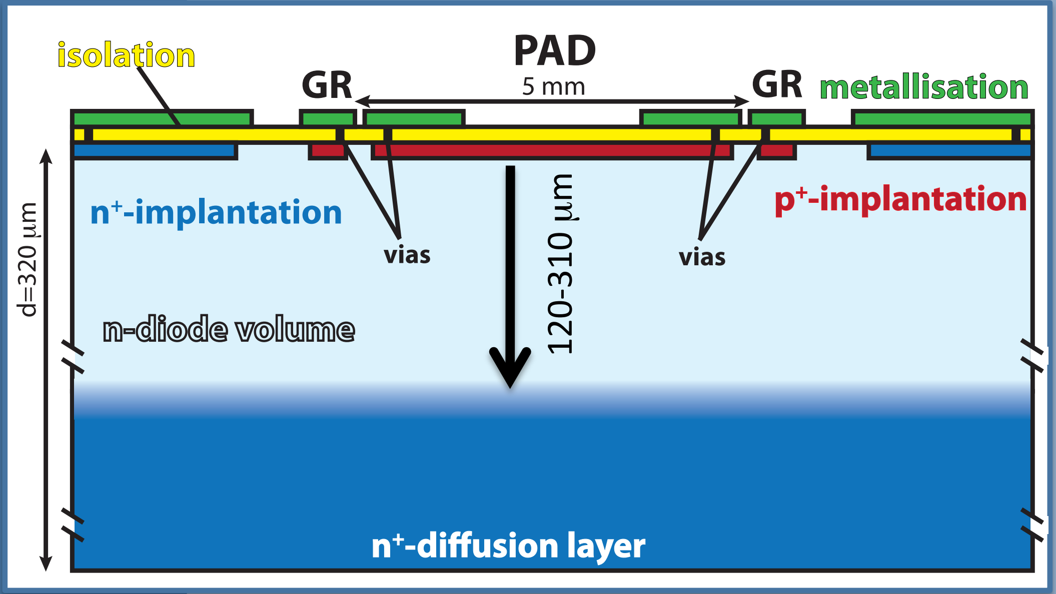
- **Float Zone (120 μm, 200 μm, 320 μm)**
- **Magnetic Czochralski (200 μm)**
- Epitaxically grown (50 μm, 70 μm, 100 μm)

Irradiation campaign:

- 1 MeV neutrons at TRIGA Reactor, Ljubljana
- 25 MeV protons at KIT, Karlsruhe

Measurements:

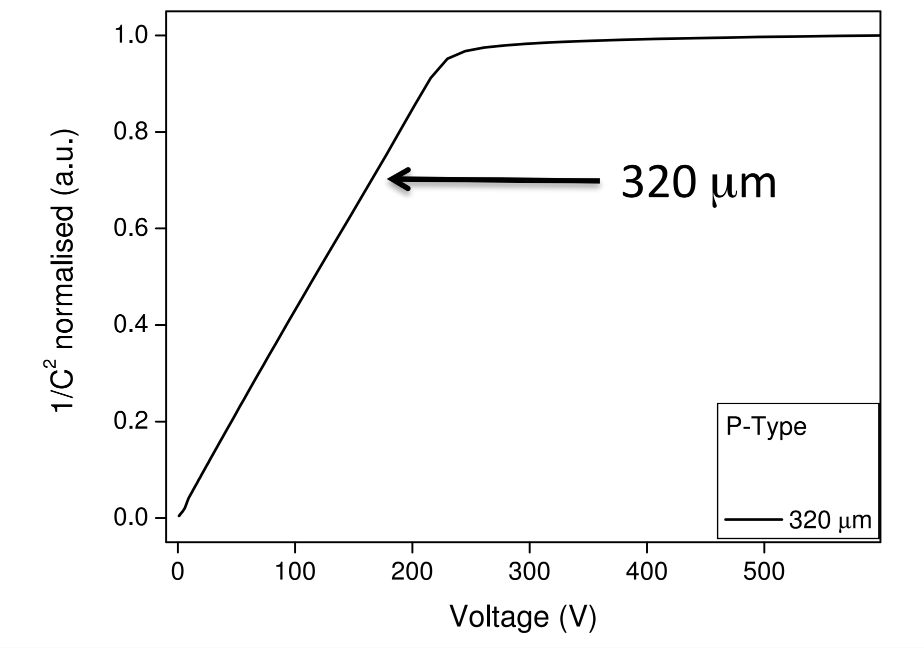
Capacitance-Voltage (C-V) & Current-Voltage Characteristics (I-V), Charge collection efficiency (CCE), Transient current technique (TCT), Si-Defektanalysen (DLTS, TSC)



Aim: Complete characterisation of available silicon materials and sensor designs

“Macroscopic” diode properties

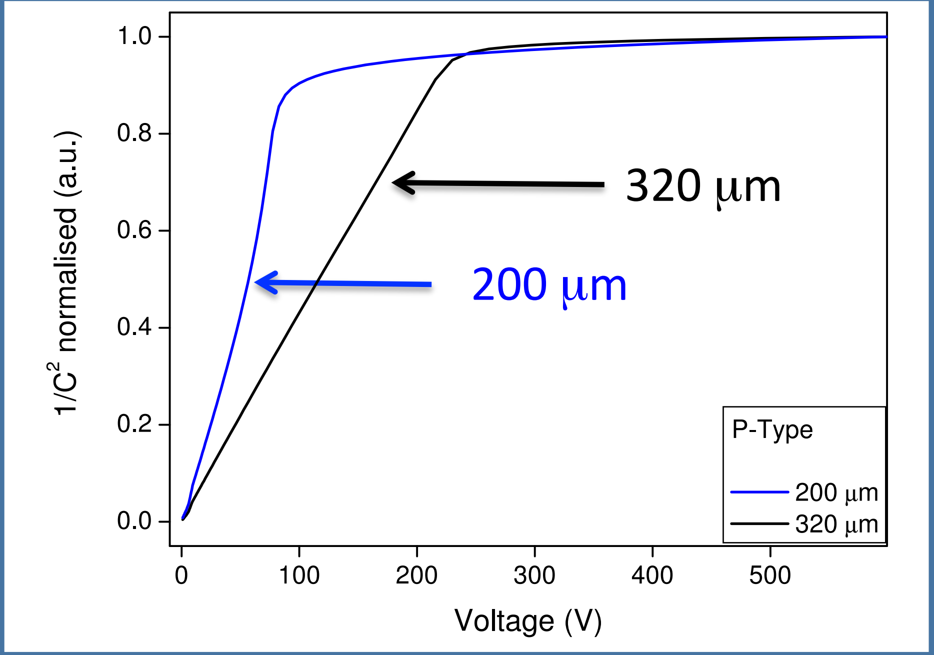
C-V measurement of p-type FZ



- 320 µm: “*ideal*” C-V curve

“Macroscopic” diode properties

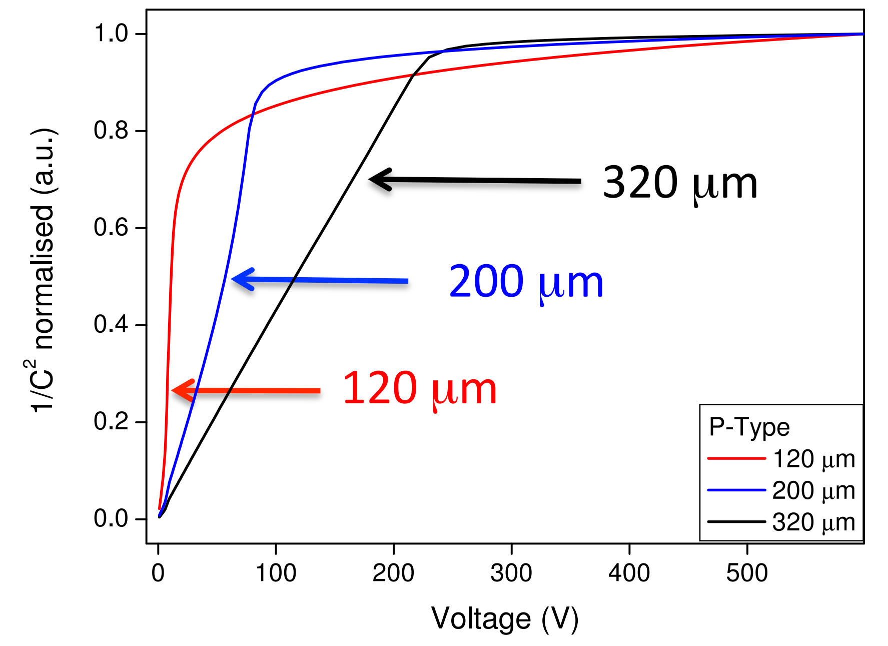
C-V measurement of p-type FZ



- 320 μm: “*ideal*” C-V curve
- 200 μm: no plateau

“Macroscopic” diode properties

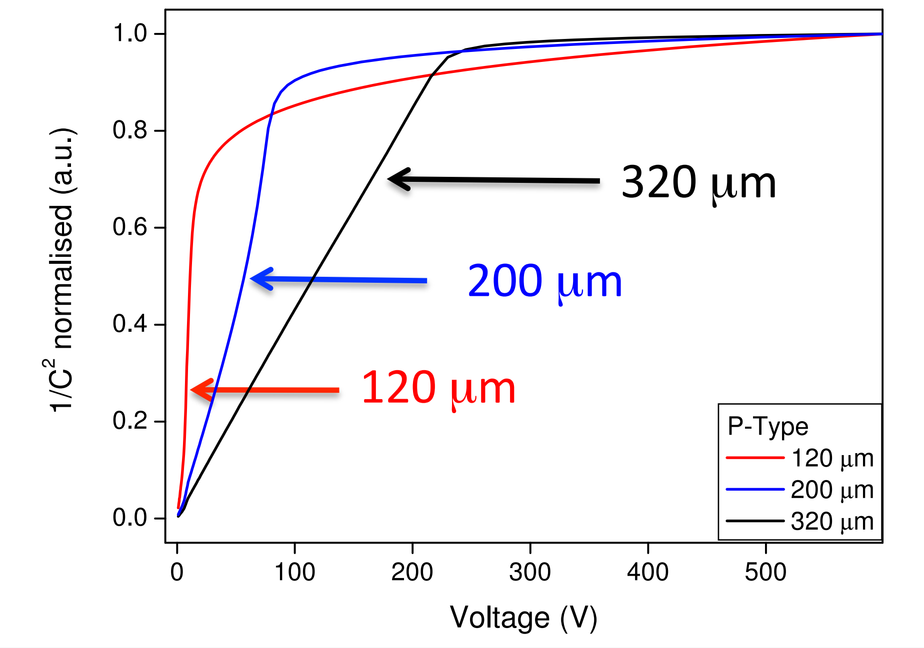
C-V measurement of p-type FZ



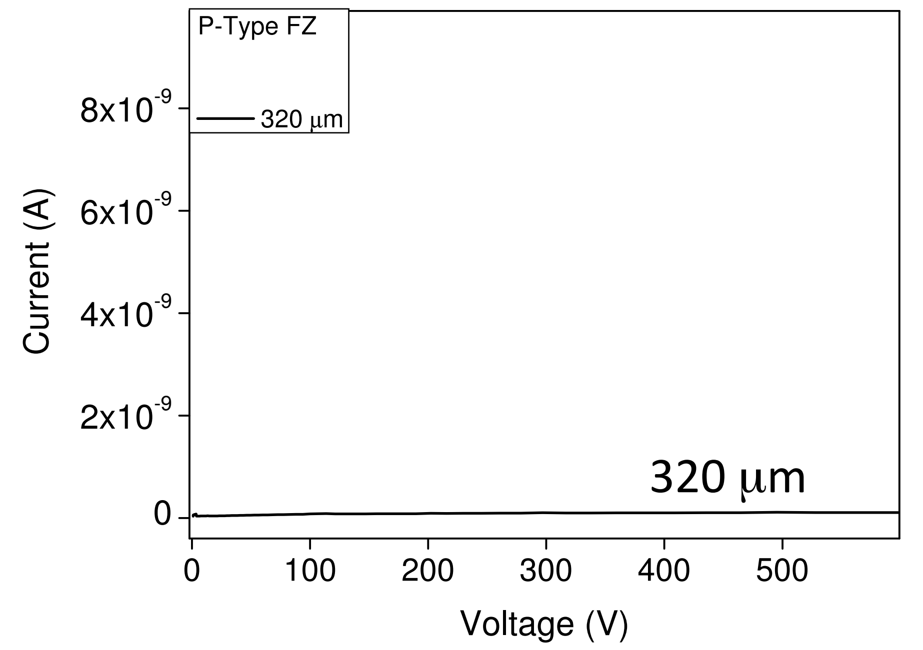
- 320 μm: “*ideal*” C-V curve
- 200 μm: no plateau
- 120 μm: no plateau

“Macroscopic” diode properties

C-V measurement of p-type FZ



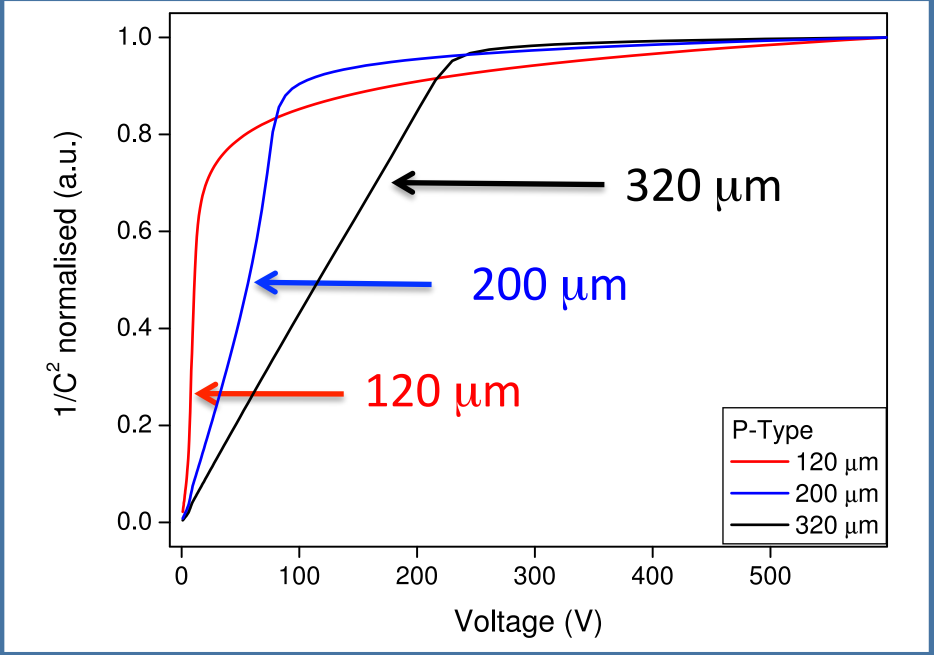
I-V characteristics of p-type FZ



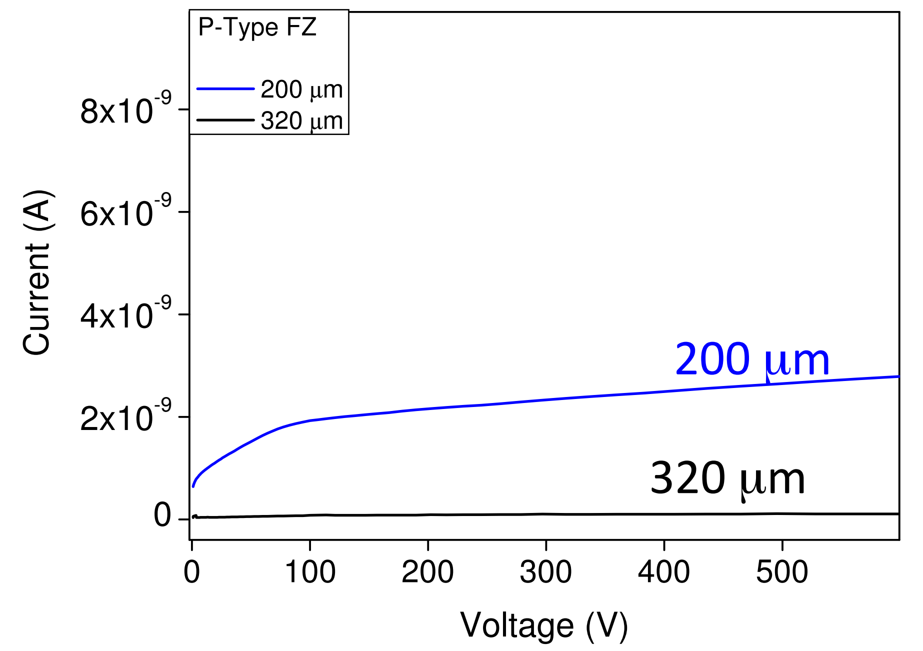
- 320 µm: “*ideal*” C-V curve
- 200 µm: no plateau
- 120 µm: no plateau

“Macroscopic” diode properties

C-V measurement of p-type FZ



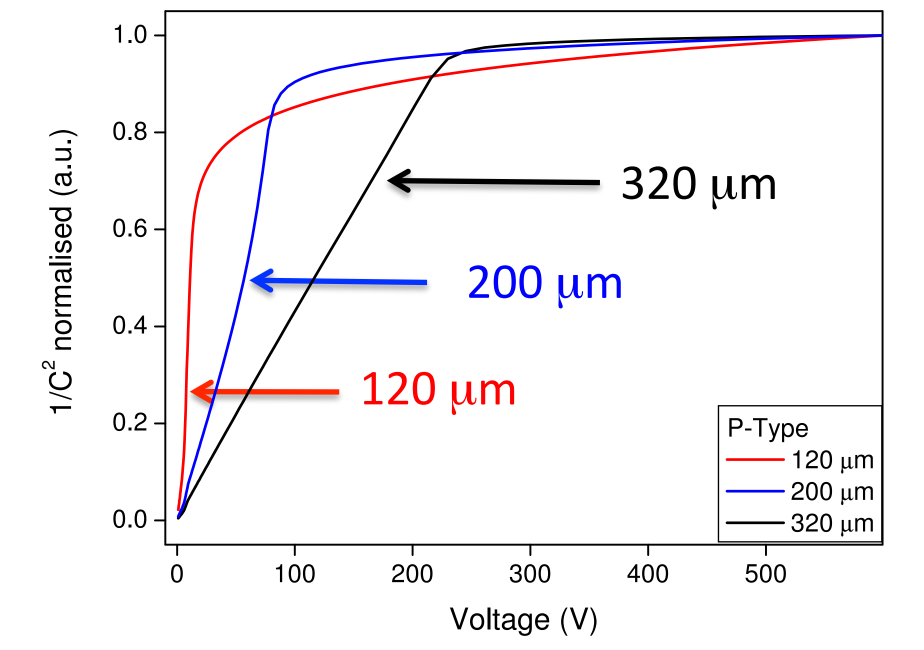
I-V characteristics of p-type FZ



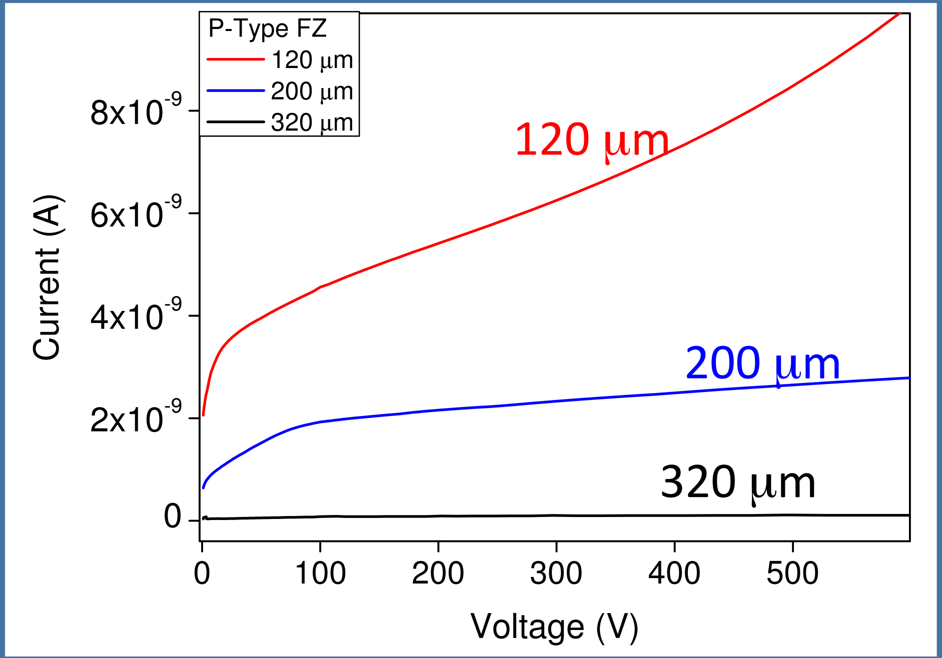
- 320 µm: “*ideal*” C-V curve
- 200 µm: no plateau
- 120 µm: no plateau

“Macroscopic” diode properties

C-V measurement of p-type FZ



I-V characteristics of p-type FZ

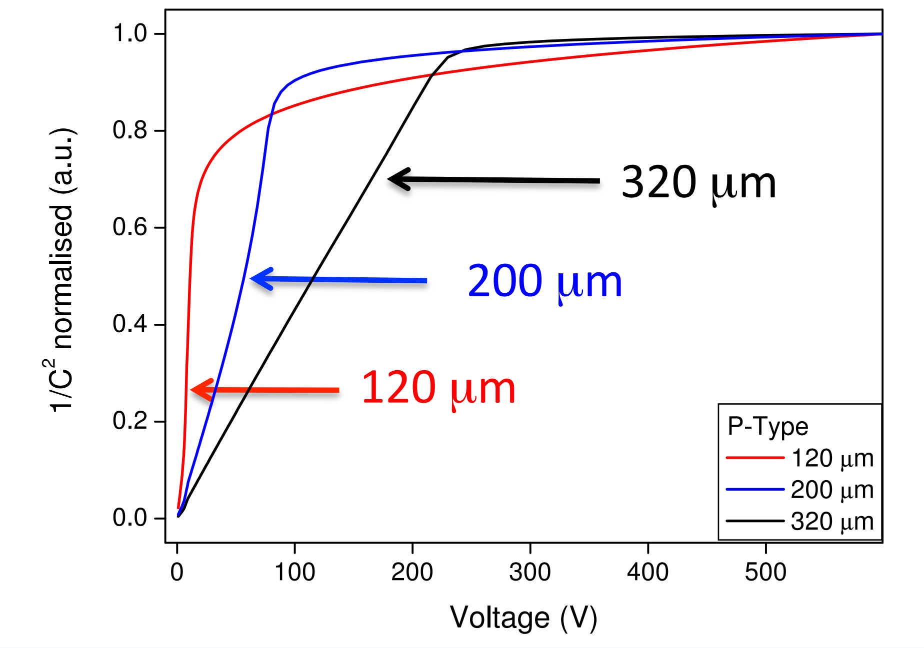


- 320 µm: “*ideal*” C-V curve
- 200 µm: no plateau
- 120 µm: no plateau

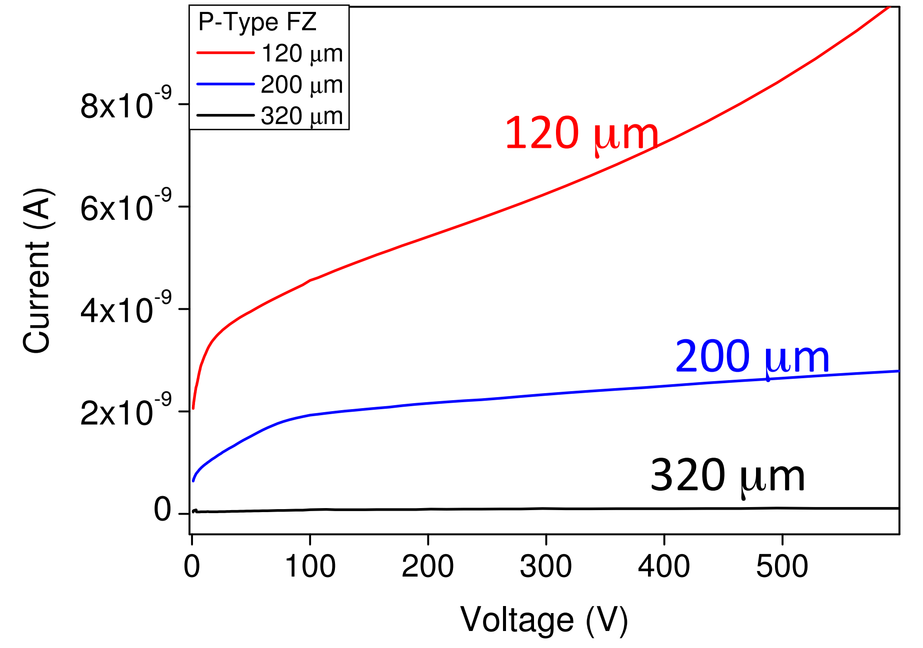
- Unusual high currents for thin diodes

“Macroscopic” diode properties

C-V measurement of p-type FZ



I-V characteristics of p-type FZ



Possible reasons:

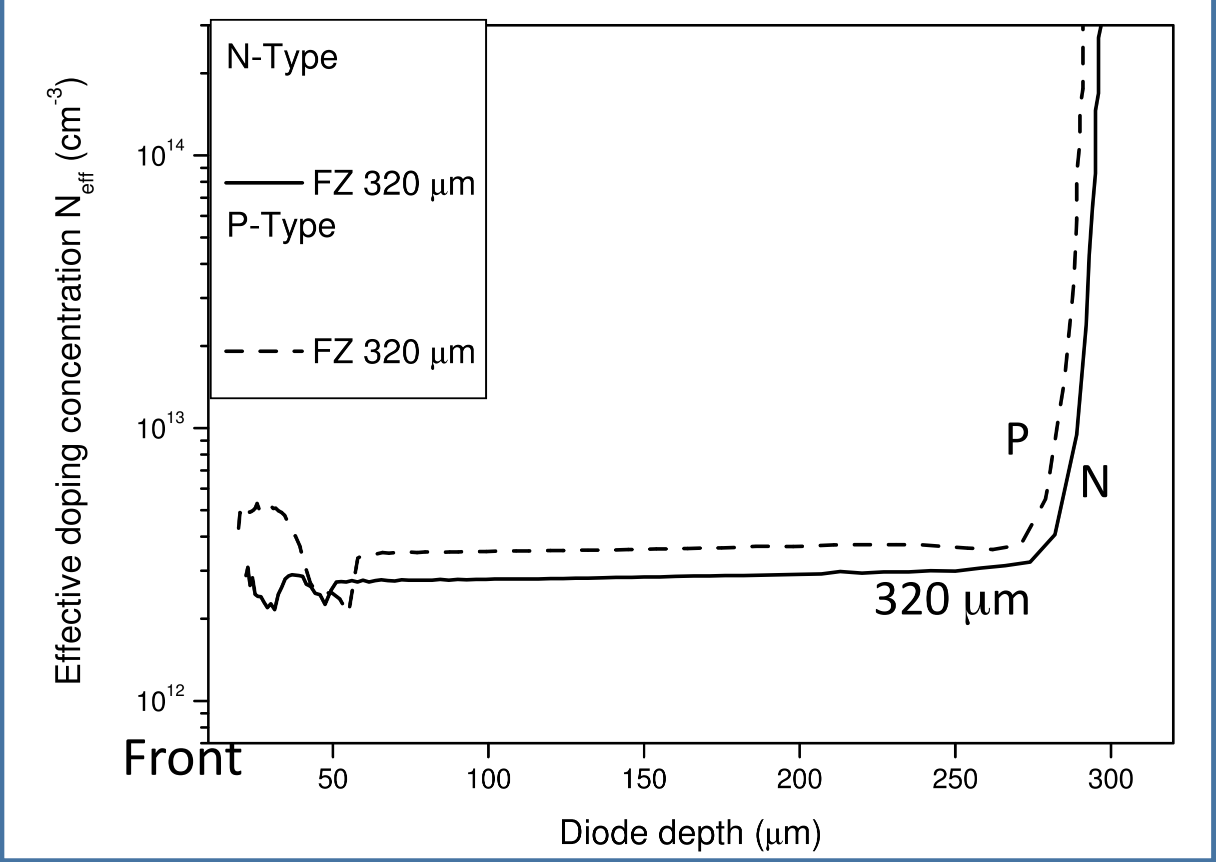
- Process induced defects: Thermal donors, stacking faults?
- Surface or „edge“ effects (not probable)

Doping profile

Calculation of depth profile via:

$$\frac{d(1/C^2)}{dV} = -\frac{2}{A^2 \varepsilon \varepsilon_0 q_0 \left| N_{eff} \right|}$$

N_{eff} – depth profile from C-V characteristics



Doping profile

Calculation of depth profile via:

$$\frac{d(1/C^2)}{dV} = -\frac{2}{A^2 \varepsilon \varepsilon_0 q_0 |N_{eff}|}$$

N_{eff} – Depth profile

N-type sensors:

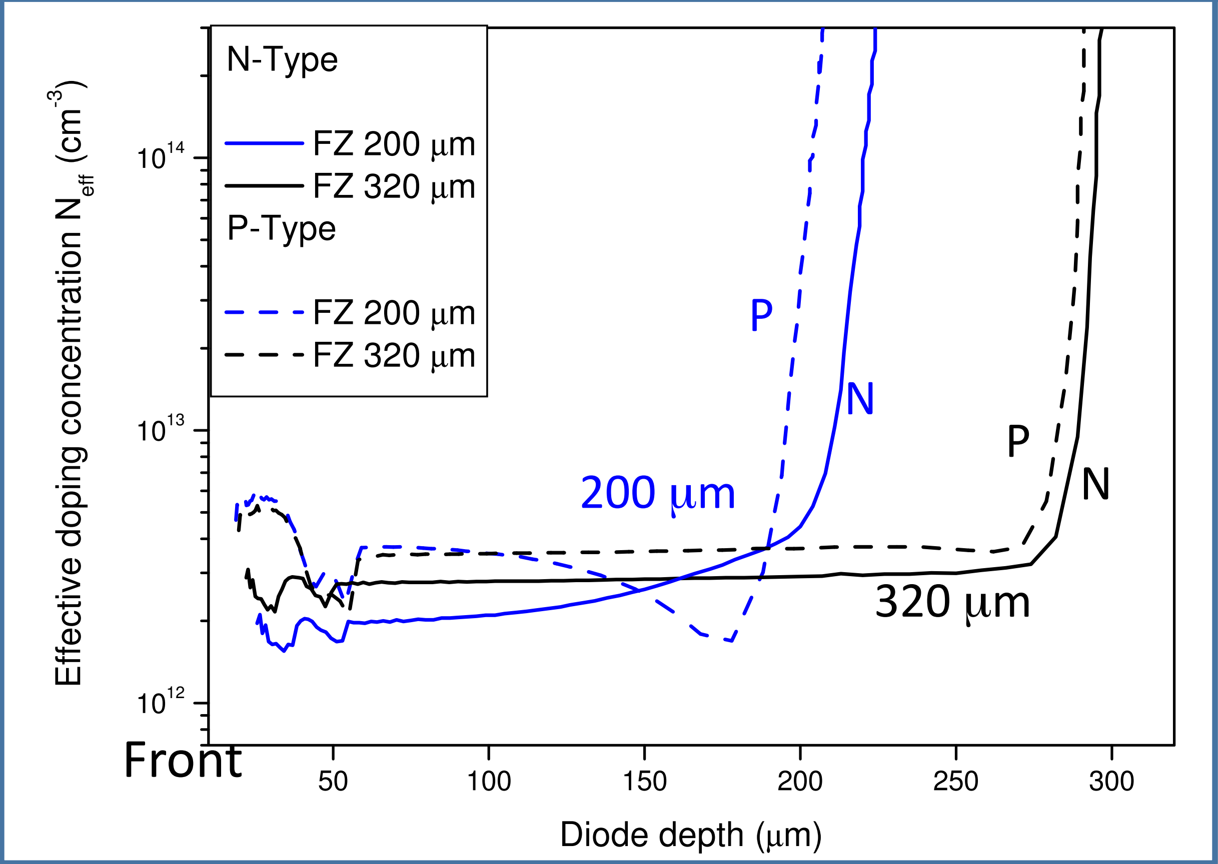
- Increase of doping concentration towards rear side implantation

P-type sensors:

- Decrease of doping concentration at rear side implantation

Pronounced effect in thin sensors

N_{eff} – depth profile from C-V characteristics



Doping profile

Calculation of depth profile via:

$$\frac{d(1/C^2)}{dV} = -\frac{2}{A^2 \varepsilon \varepsilon_0 q_0 |N_{eff}|}$$

N_{eff} – Depth profile

N-type sensors:

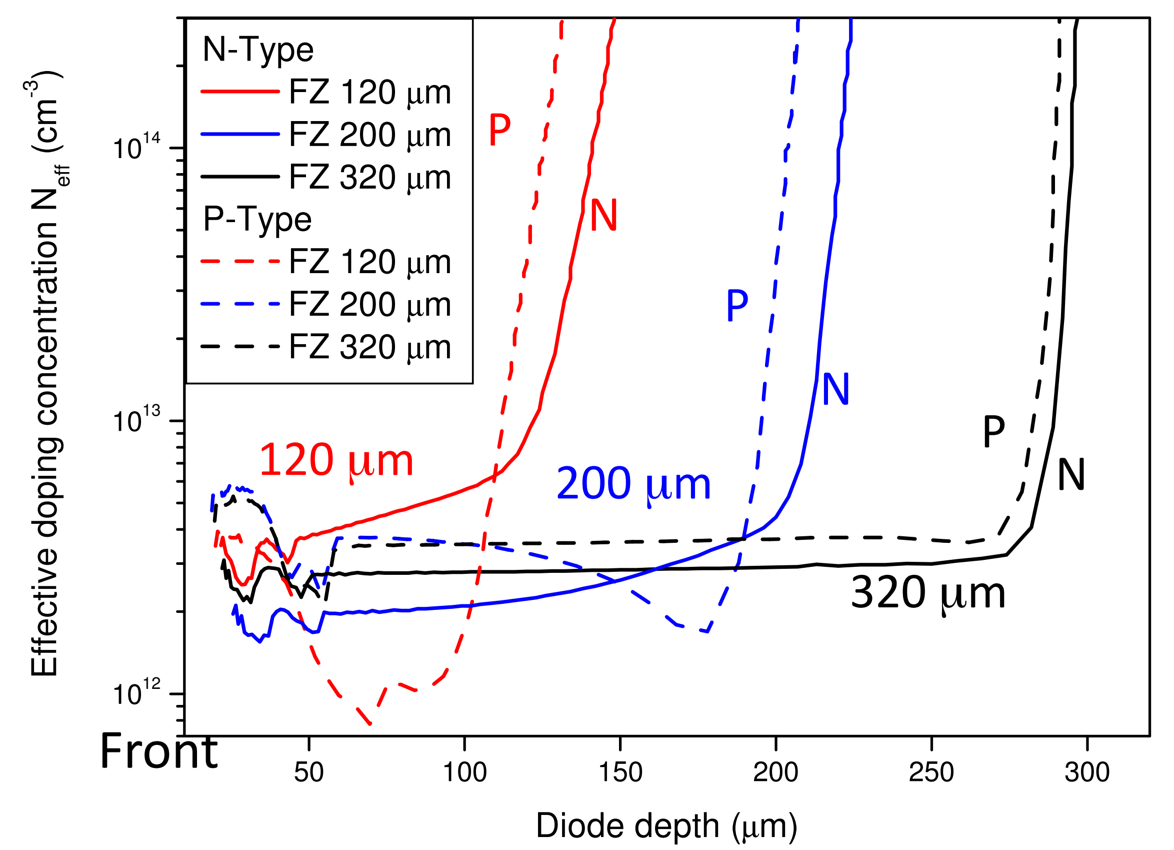
- Increase of doping concentration towards rear side implantation

P-type sensors:

- Decrease of doping concentration at rear side implantation

Pronounced effect in thin sensors

N_{eff} – depth profile from C-V characteristics



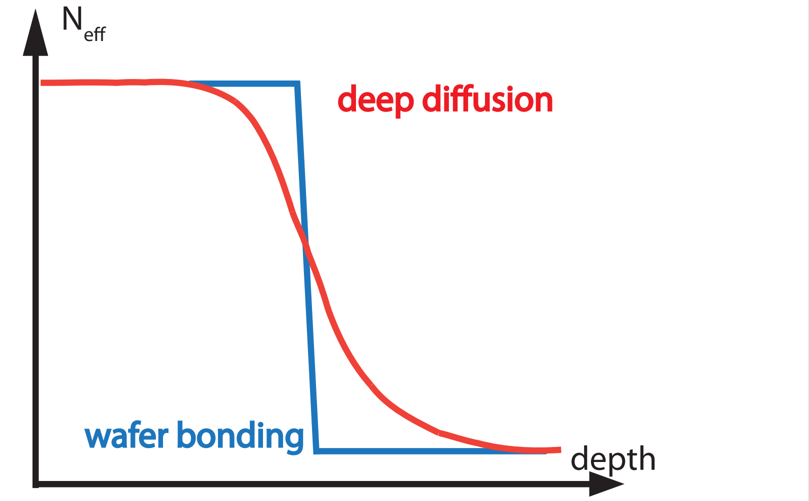
Inhomogeneous doping profiles in thin diodes

Doping profile

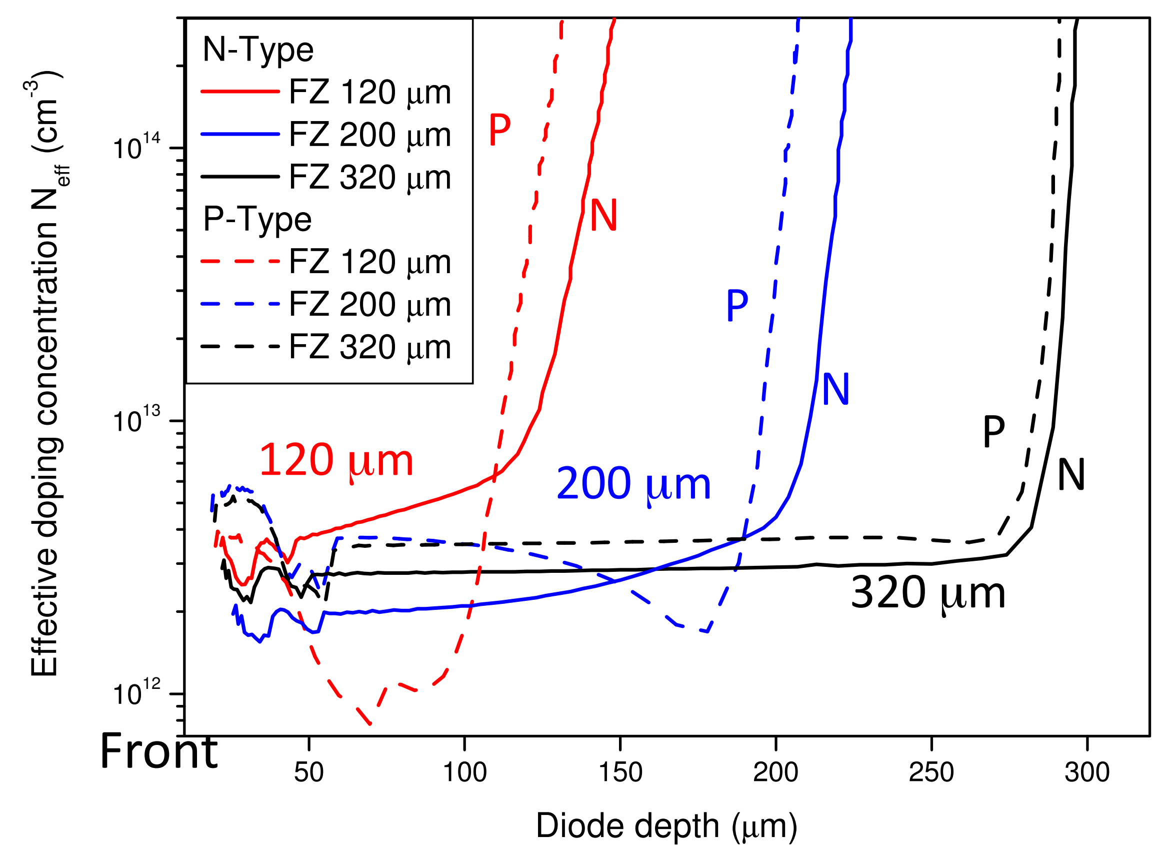
Calculation of depth profile via:

$$\frac{d(1/C^2)}{dV} = -\frac{2}{A^2 \varepsilon \varepsilon_0 q_0 \left|N_{eff}\right|}$$

Reason: *deep diffusion* process



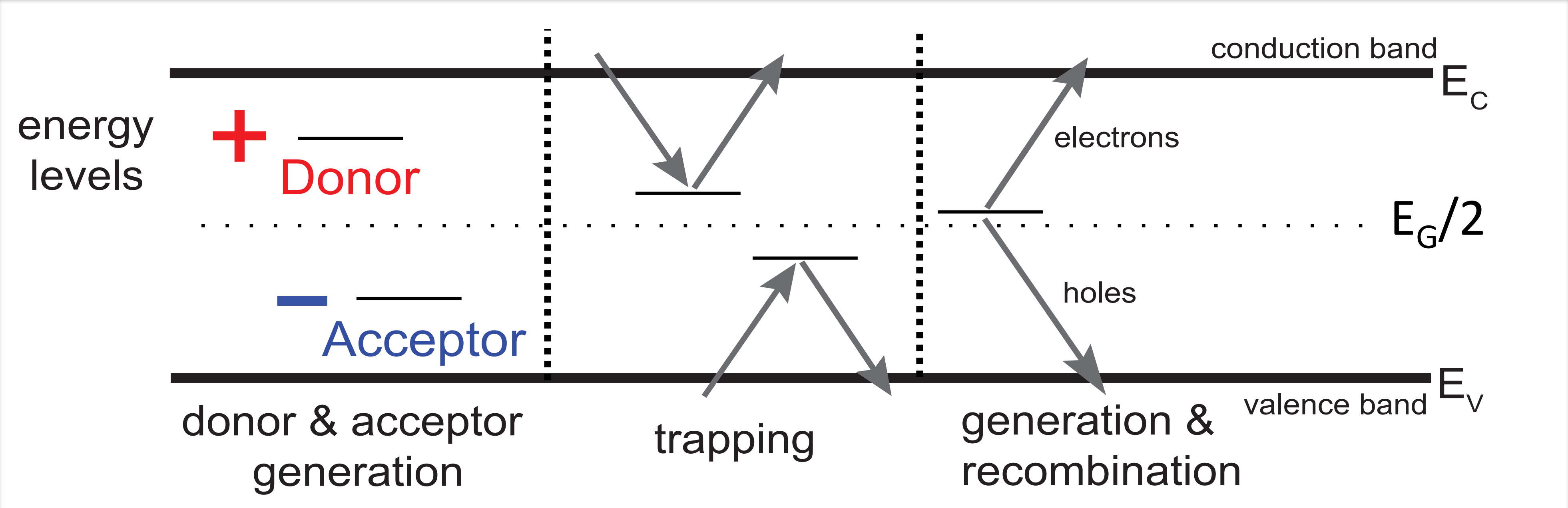
N_{eff} – depth profile from C-V characteristics



Inhomogeneous doping profiles in thin diodes

Impact of defects on detector properties

Determined by Shockley-Read-Hall statistics



Charged defects (at RT)

→ N_{eff}, V_{dep}

(Acceptors in the lower half and donors in the upper half of the band gap)

Deep defects

→ CCE

(Shallow defects do not contribute due to detrapping)

Levels close to midgap

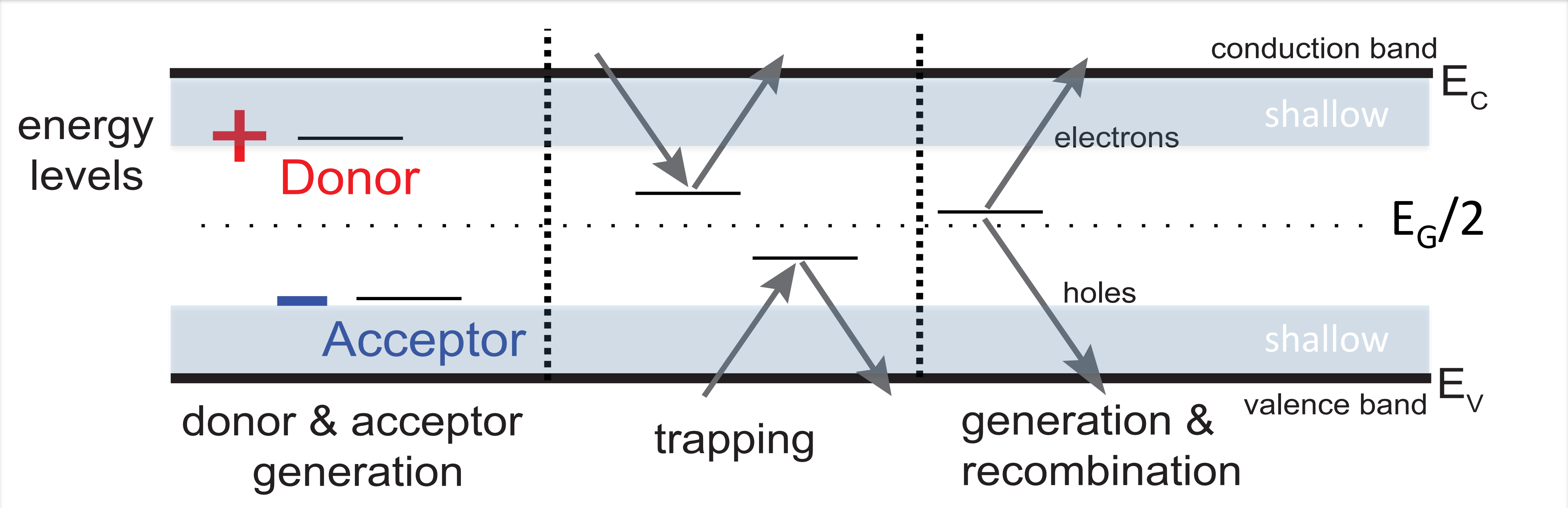
→ I_{leak} (NOISE)

(Defect levels close to midgap most effective)

→ Cooling during operation helps!

Impact of defects on detector properties

Determined by Shockley-Read-Hall statistics



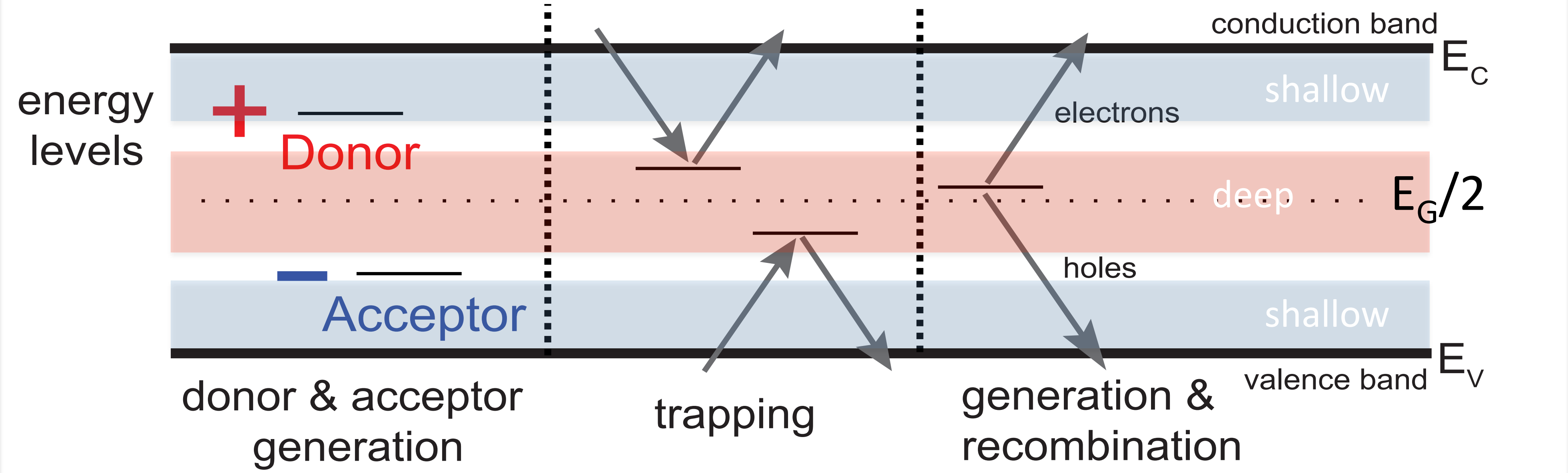
Charged defects (at RT)
→ N_{eff}, V_{dep}
(Acceptors in the lower half and donors in the upper half of the band gap)

Deep defects
→ CCE
(Shallow defects do not contribute due to detrapping)

Levels close to midgap
→ I_{leak} (NOISE)
(Defect levels close to midgap most effective)
→ Cooling during operation helps!

Impact of defects on detector properties

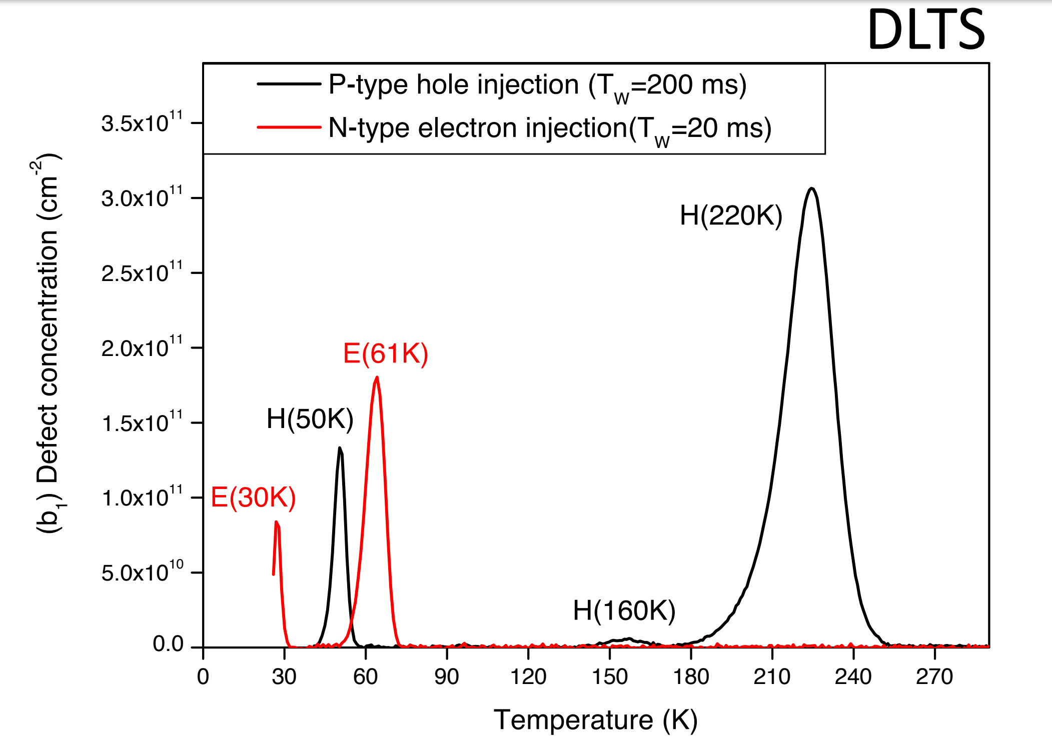
Determined by Shockley-Read-Hall statistics



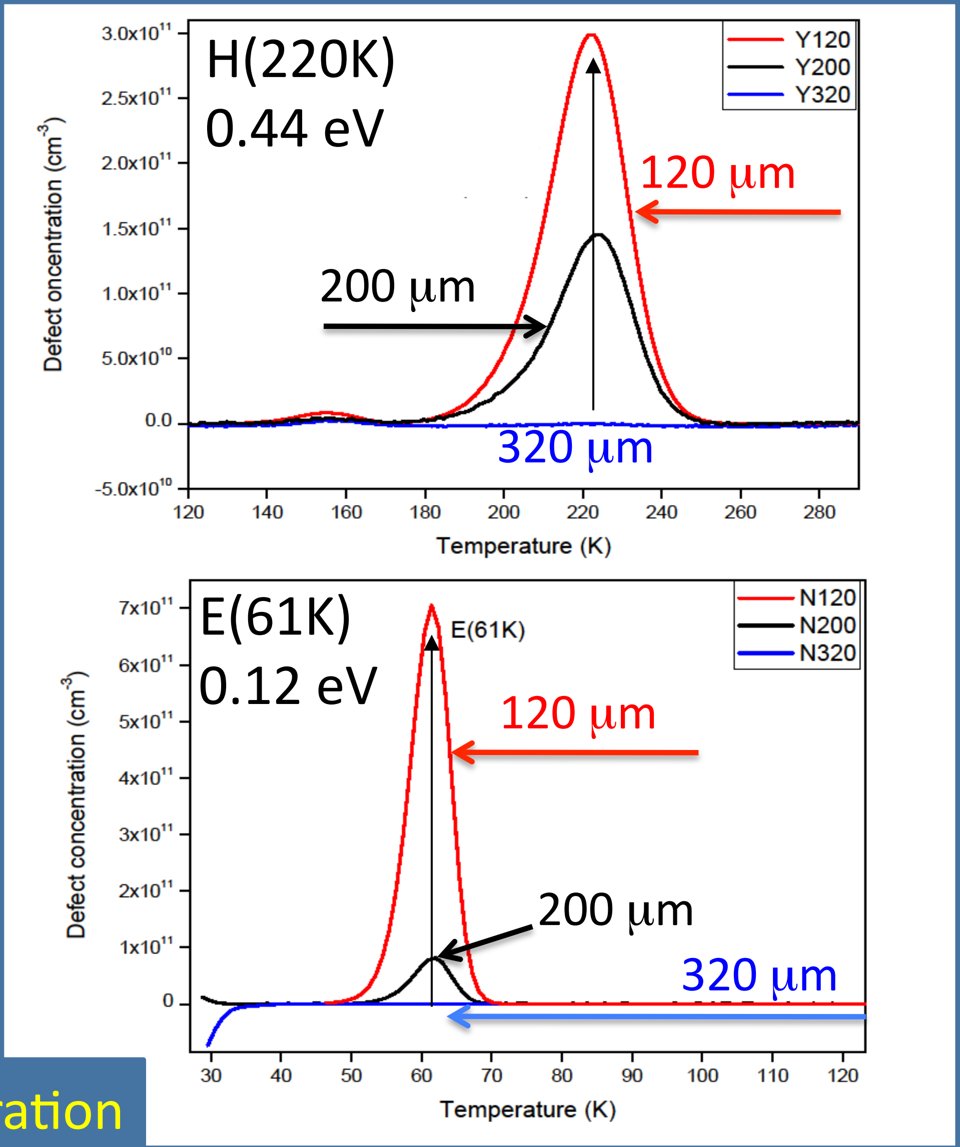
Charged defects (at RT) → N_{eff}, V_{dep} (Acceptors in the lower half and donors in the upper half of the band gap)	Deep defects → CCE (Shallow defects do not contribute due to detrapping)	Levels close to midgap → I_{leak} (NOISE) (Defect levels close to midgap most effective) → Cooling during operation helps!

Process induced material defects

Crystal defects in FZ silicon



H(220K) in p-type: Current generator at 0.44 eV
E(61K): Donor, generation of pos. space charge

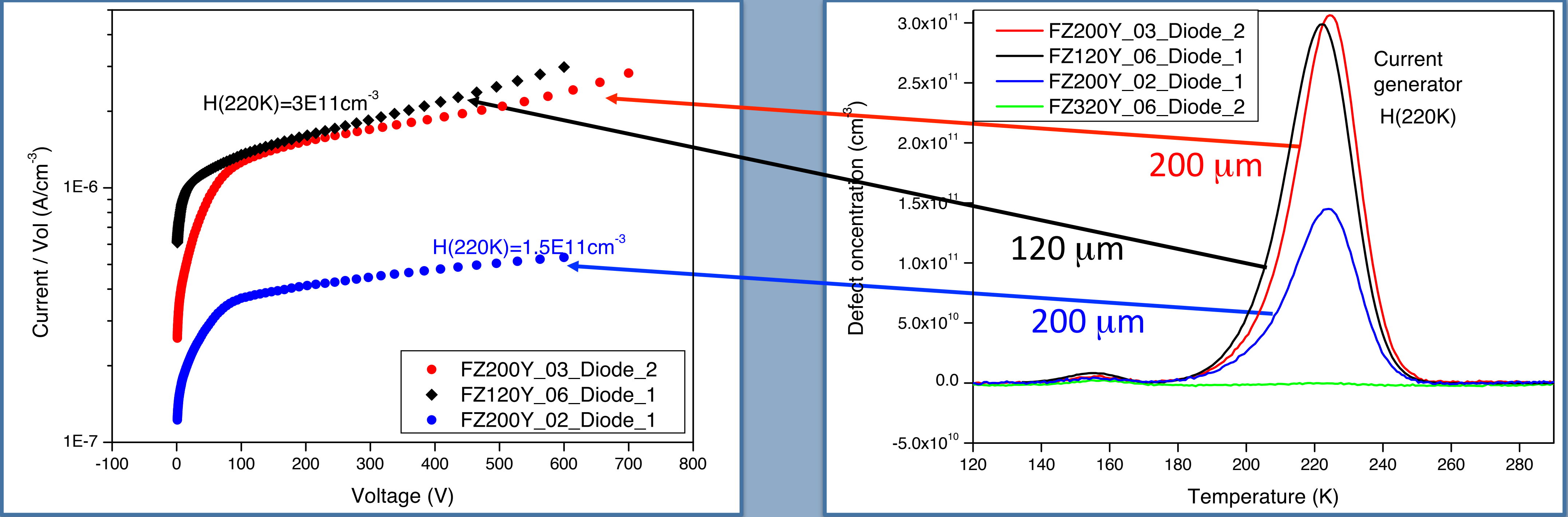


Correlation of diode thickness and defect concentration

H(220K) generates current

I-V measurements

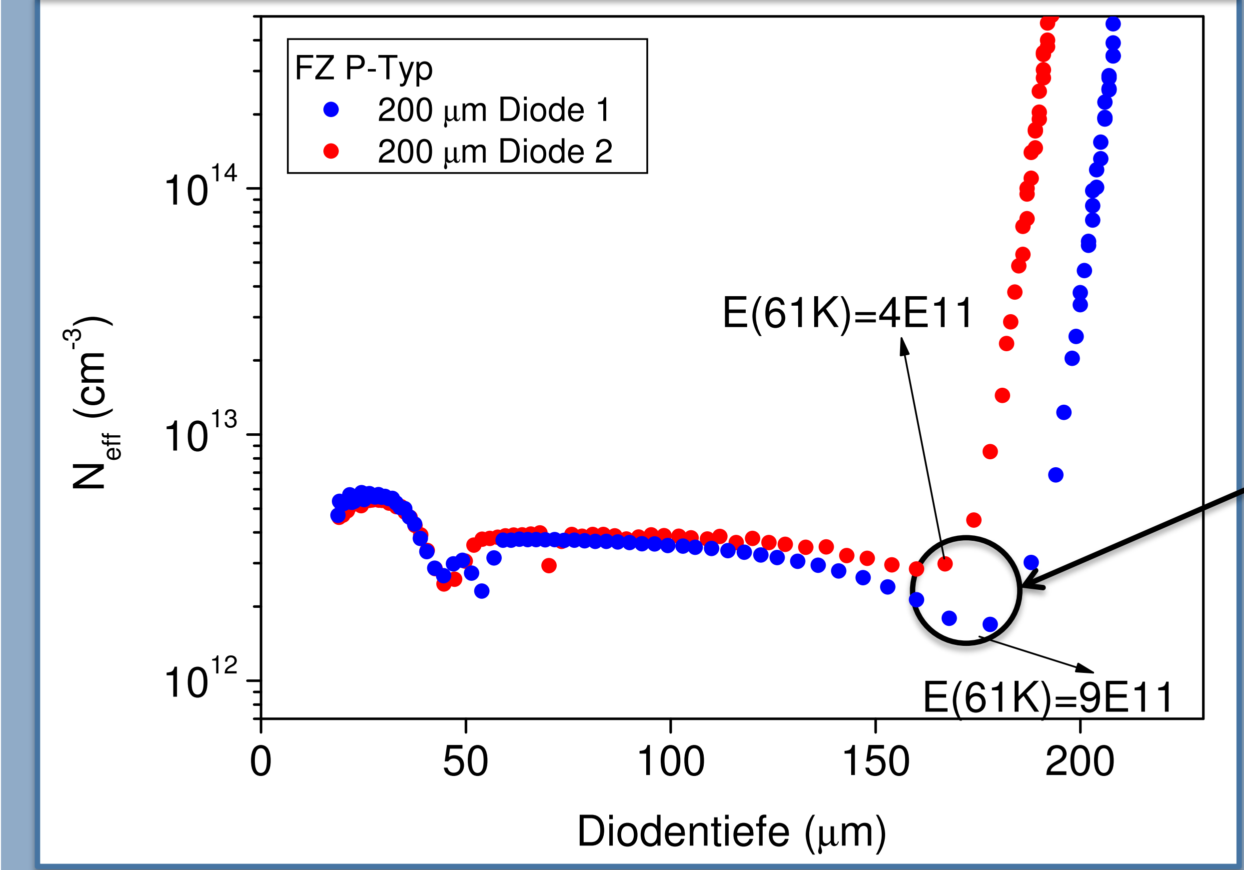
DLTS measurements



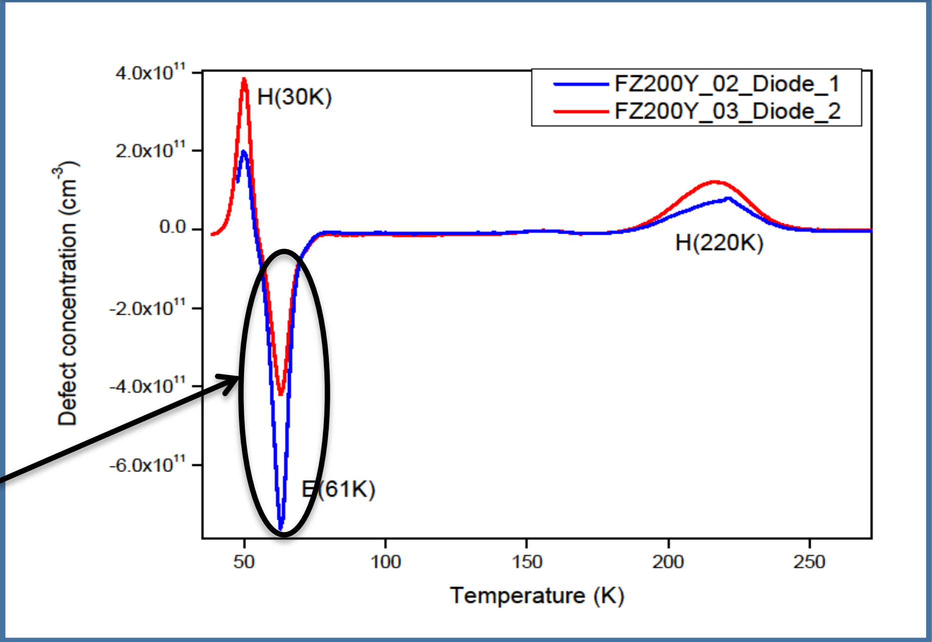
- Defect concentration scales with current generation
- Defects explain diode properties!

Influence of the E(61K) donor

N_{eff} doping profile of p-type FZ from C-V



Defects in p-type

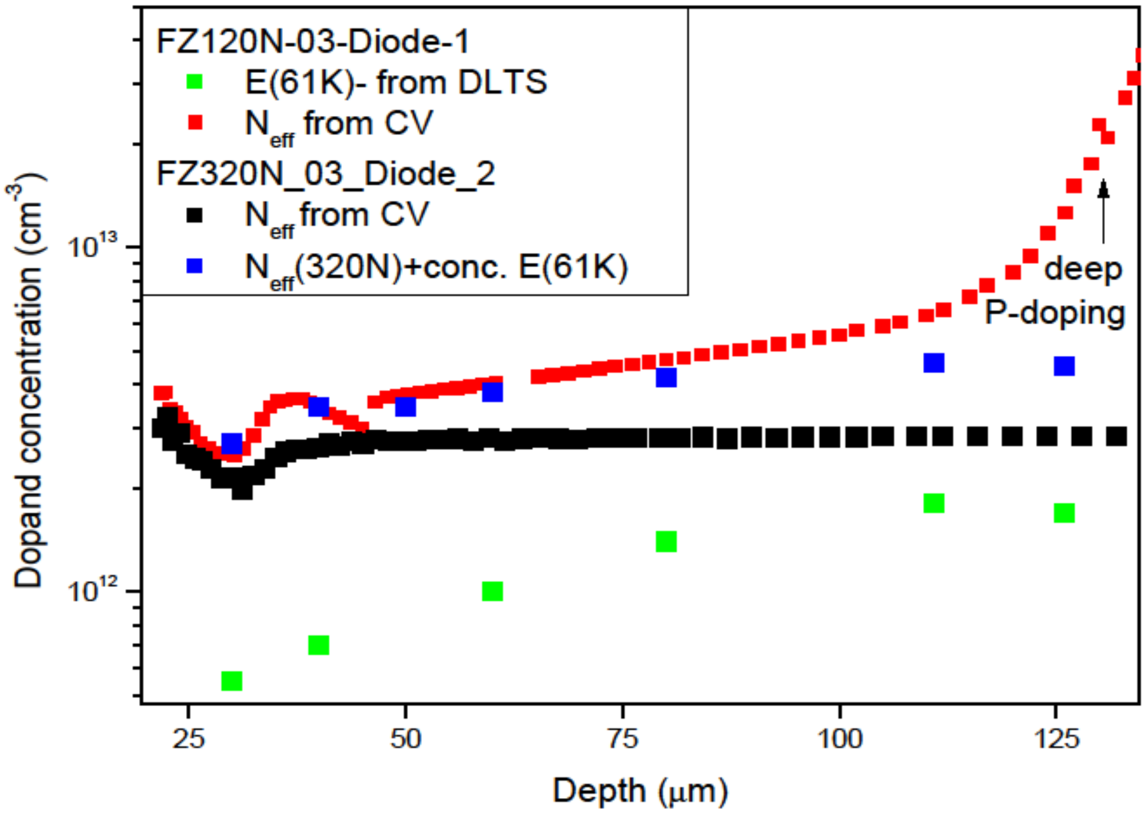


Influence of E(61K) donor:
Reduces N_{eff} in p-type material
Increase of N_{eff} in n-type material

Deep diffusion process introduces donor with influence on N_{eff}

Depth profile of the E(61K) defect

Concentration of E(61K) from DLTS



- Increase of concentration of E(61K) towards the rear side
- [E(61K)] + N_{eff} from C-V (FZ diode with d=320 μm)

- Results reproduce N_{eff} from C-V for diode with d=120 μm

E(62K) responsible for inhomegeneity at rear side!

Summary

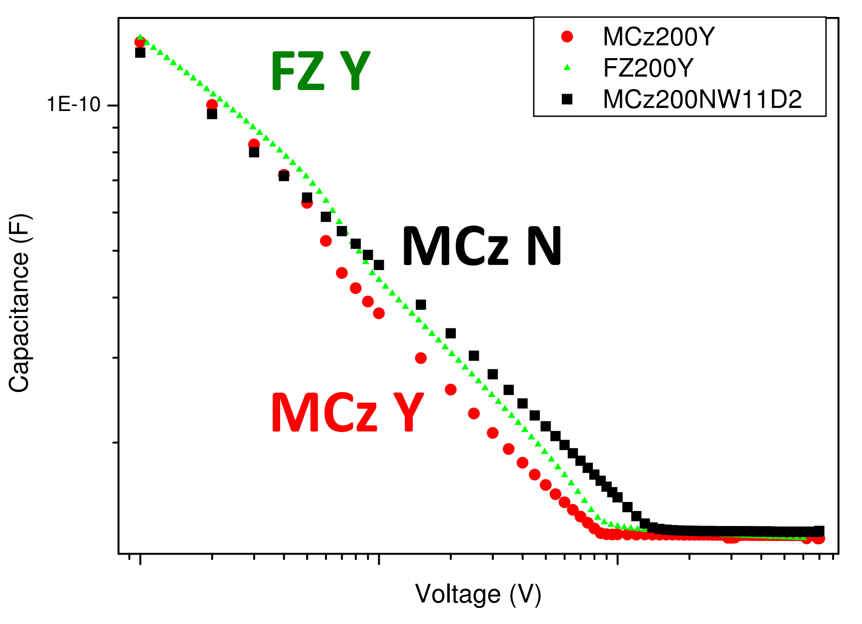
- Diodes manufactured with new process in n- and p-type FZ Si exhibit strange correlation of diode thickness and
  - effective doping concentration
  - current generation
- Material defects introduced by *deep diffusion* process were observed by means of DLTS
- Bulk defects explain
  - N_{eff} profile
  - high current in thin sensors (not the saturation behaviour)

MCz: Doping profile from C-V measurements

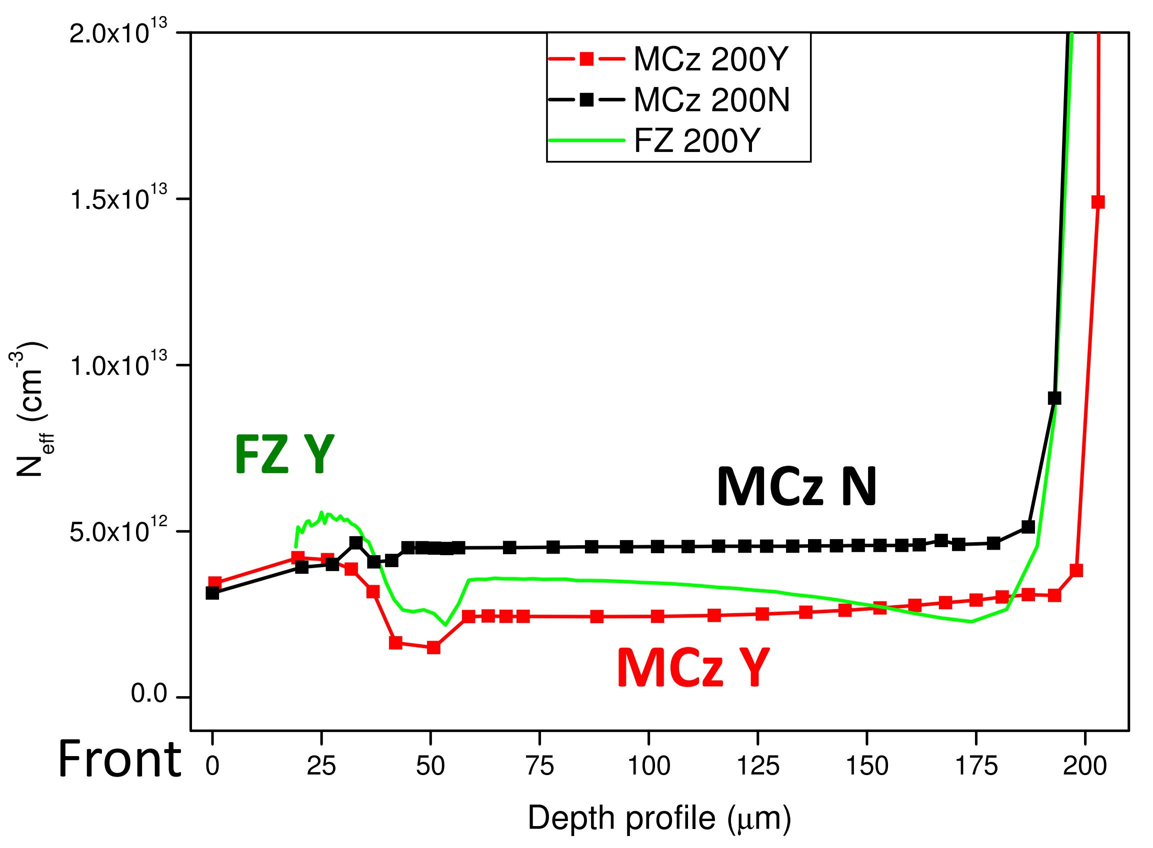
Approximation of N_{eff} depth profile from C-V:

$$\frac{d(1/C^2)}{dV} = -\frac{2}{A^2 \varepsilon\varepsilon_0 q_0 \left| N_{eff} \right|}$$

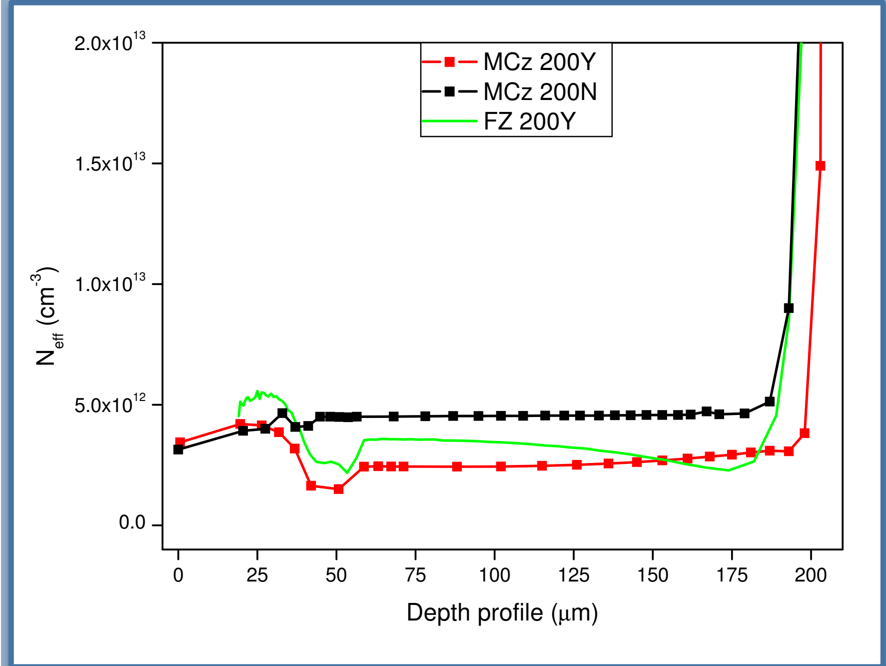
C-V Measurements for MCz and FZ



N_{eff} doping profile from C-V measurements

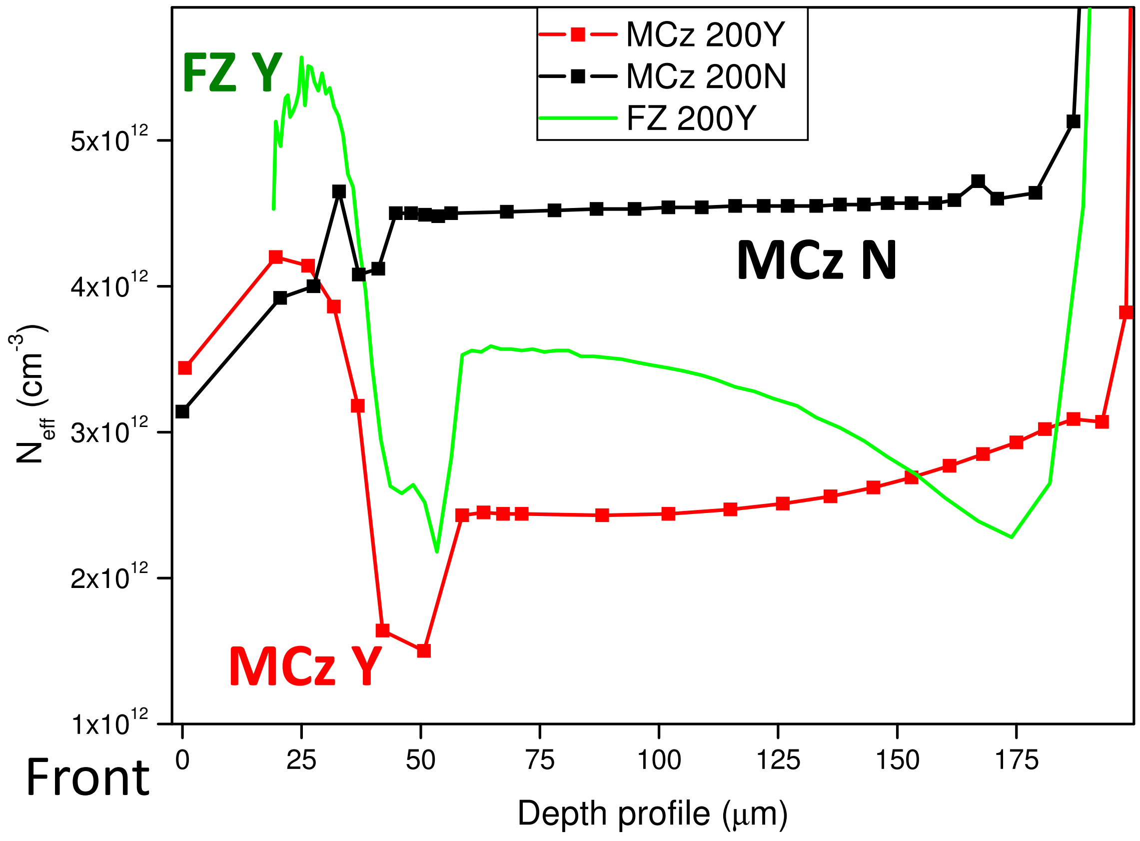


Influence of defects on the doping profile



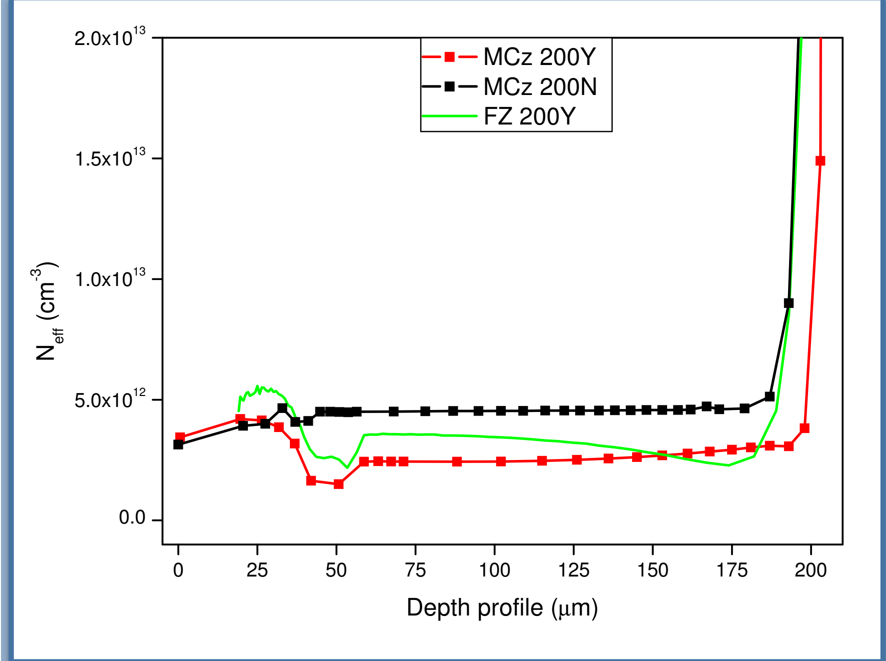
Front side disturbed also in MCz
→ Acceptor and donor contribution
→ Diffusion through diode volume?
Rear side unclear

Comparison of MCz and FZ



Process induced defects

Influence of defects on the doping profile



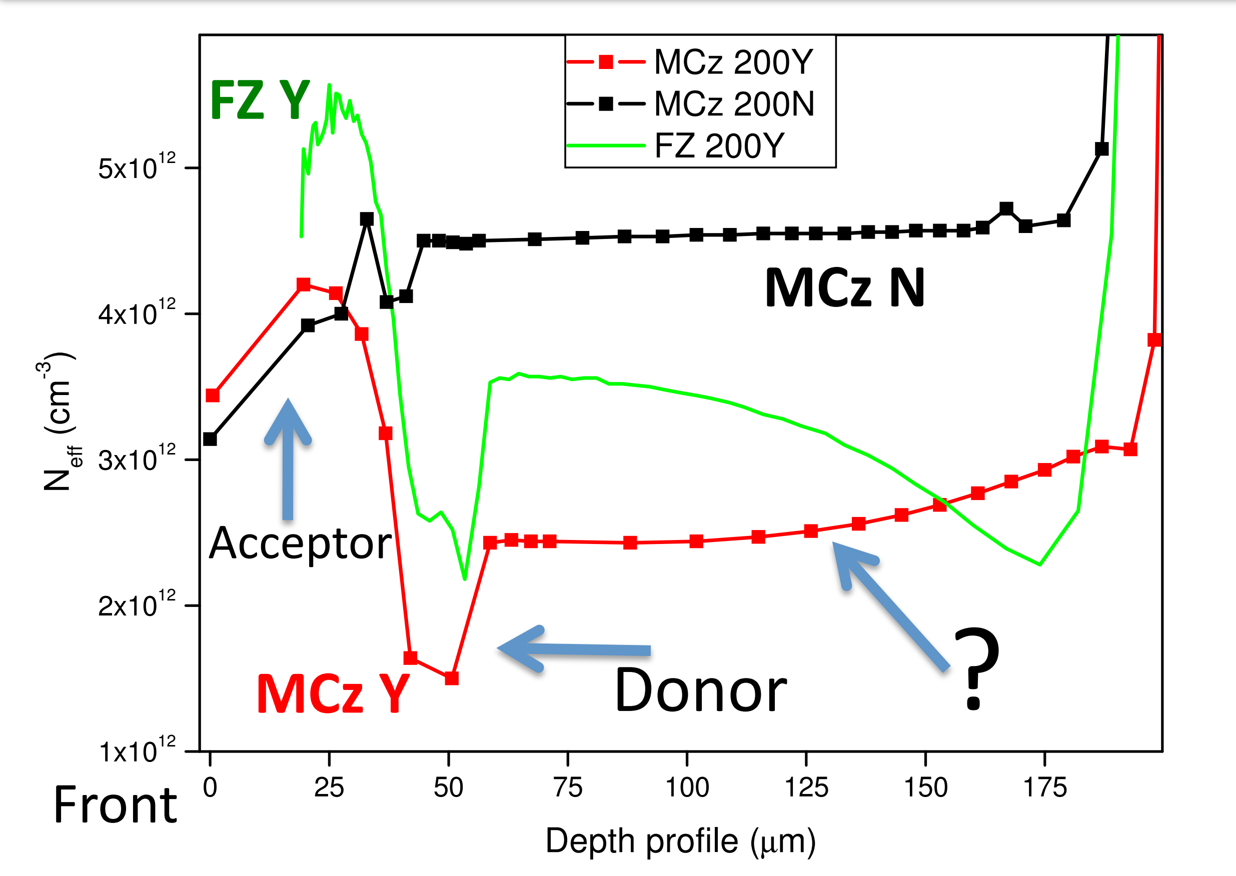
Front side disturbed also in MCz

→ Acceptor and donor contribution

→ Diffusion through diode volume?

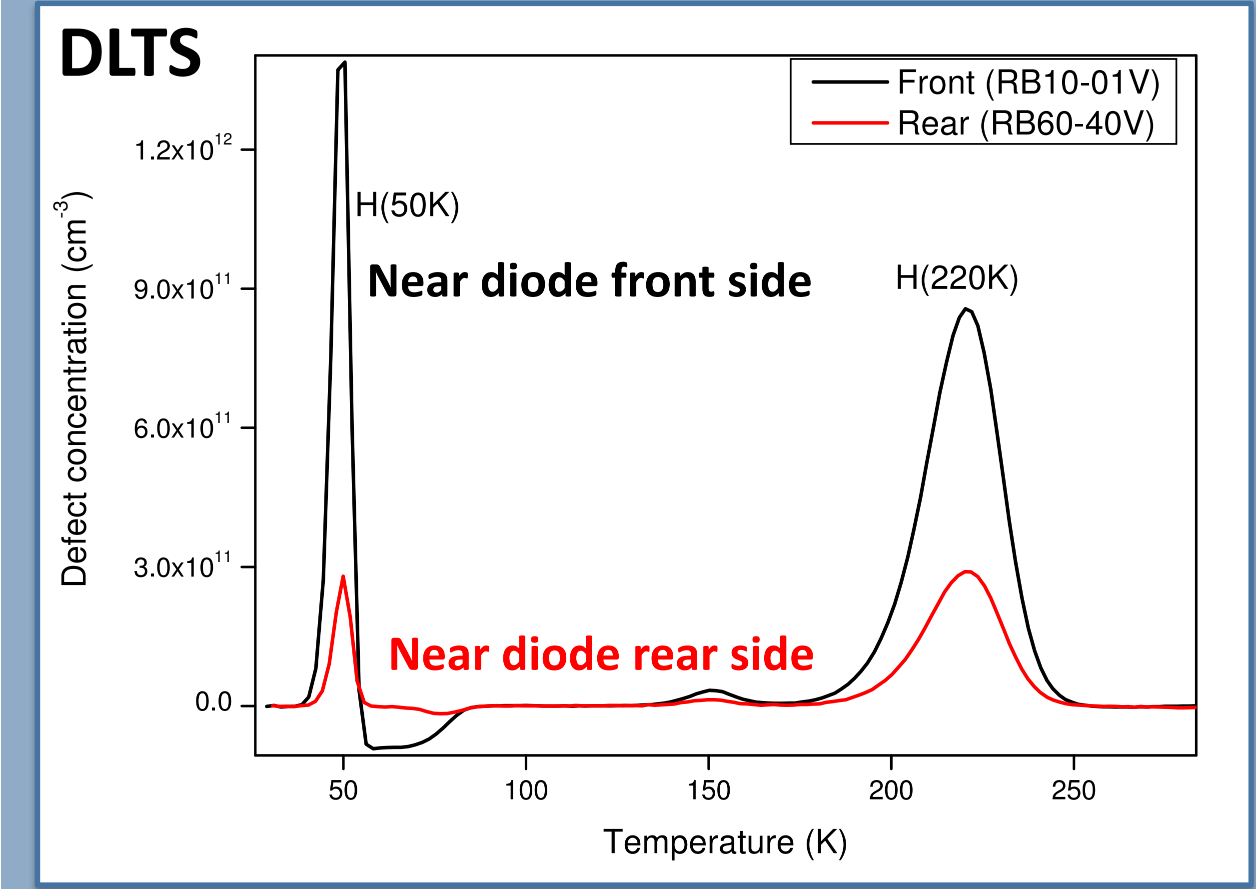
Contribution also at rear side

Comparison of MCz and FZ



Process induced defects: Thermal donors, stacking faults?

Crystal defects found in MCz200 Y (hole traps)



Hole traps:

H(220K)

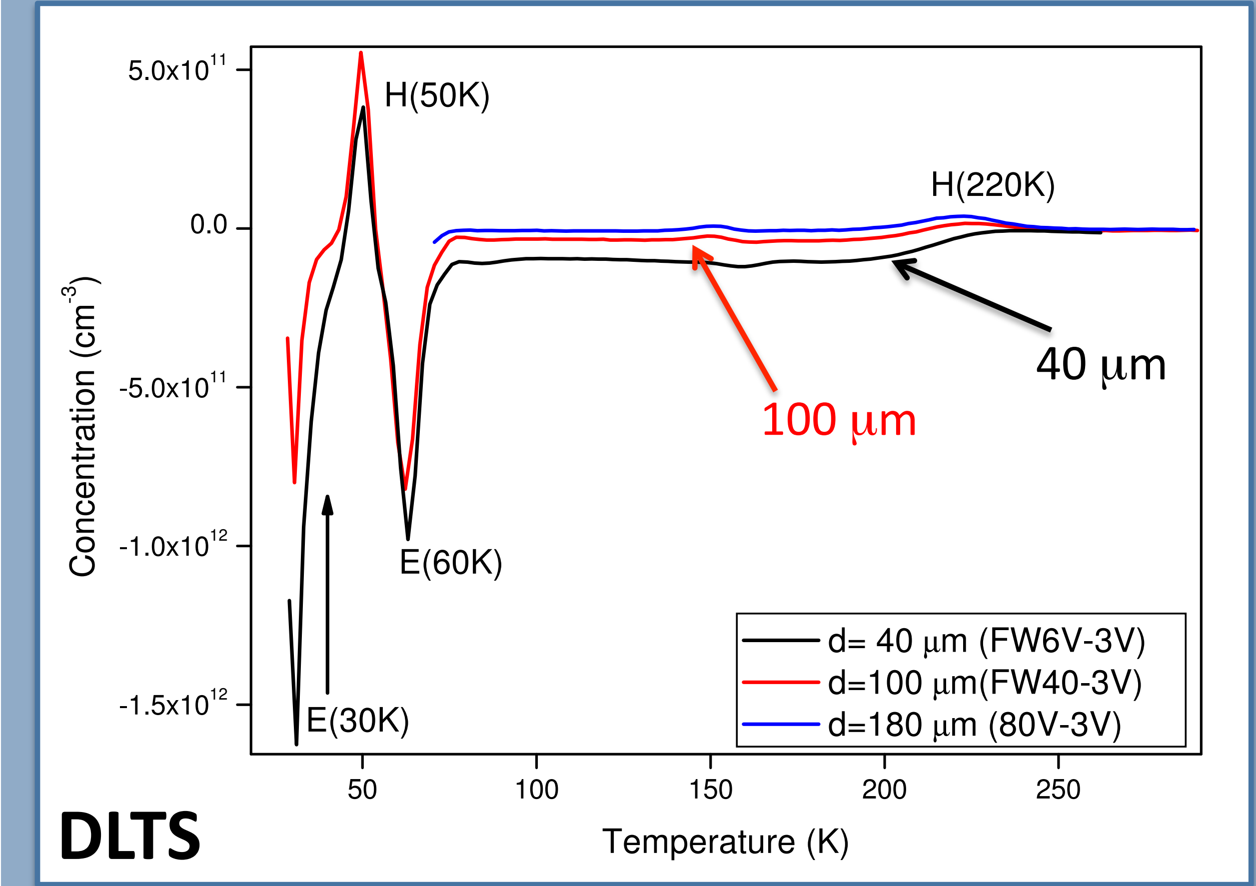
- → deep acceptor/donor (?)
- → Occupation unclear
- →Known from FZ sensors
- → Current generator
- → Conc. decrease towards rear side

H(50K)

- → shallow acceptor (?)
- → Known from FZ
- → High concentration at front side
- → Influence on N_{eff} at front

High defect concentrations at front side of diode

Crystal defects found in MCz200 Y (electron traps)



Electron traps:

E(60K)

→ shallow donor

→Known from FZ

→ Concentration unclear

E(30K)

→ very shallow donor (to be verified)

→ Known from FZ

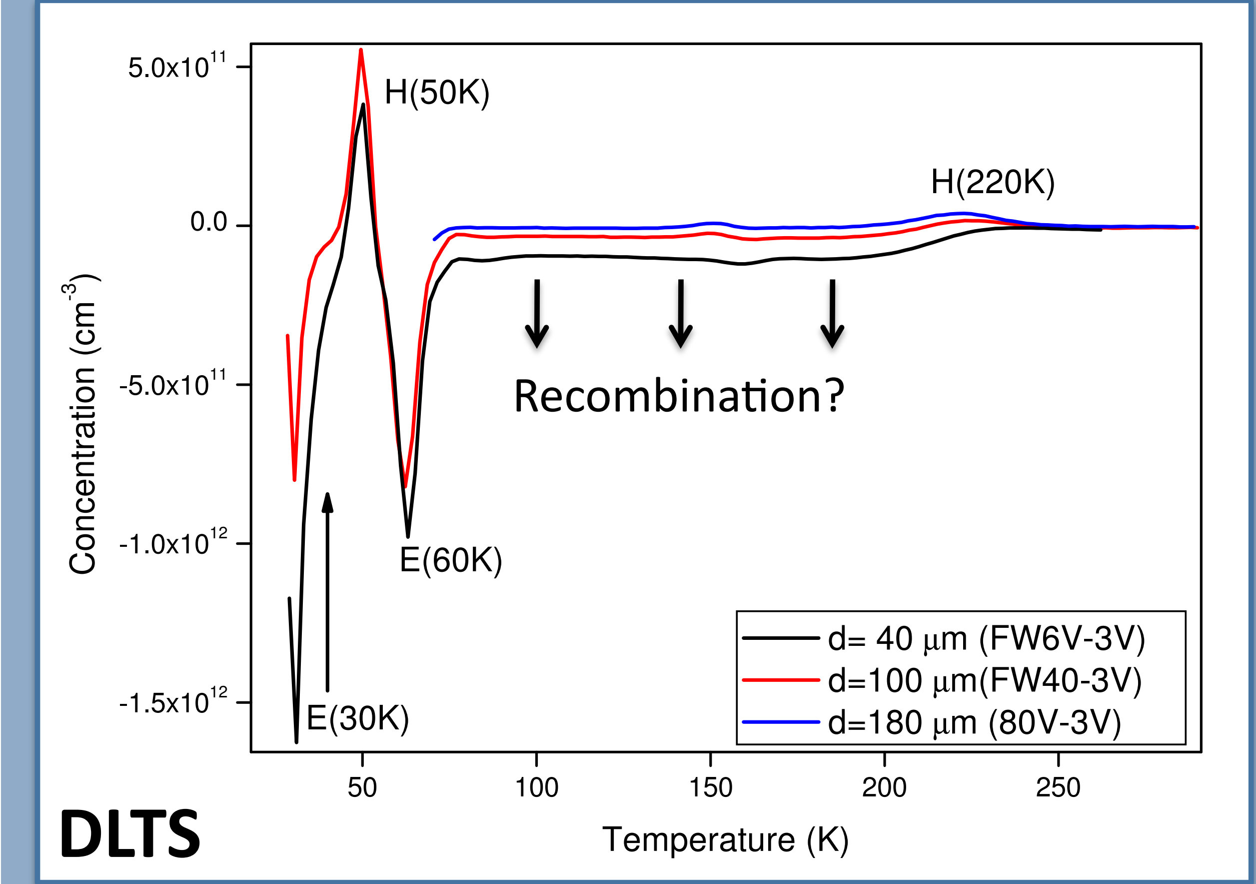
→ High concentration at front side

Strange offset below 220K

→ Recombination?

Some electron traps with impact on N_{eff}

Crystal defects found in MCz200 Y (electron traps)



Electron traps:

E(60K)

→ shallow donor

→ Known from FZ

→ Concentration unclear

E(30K)

→ very shallow donor (to be verified)

→ Known from FZ

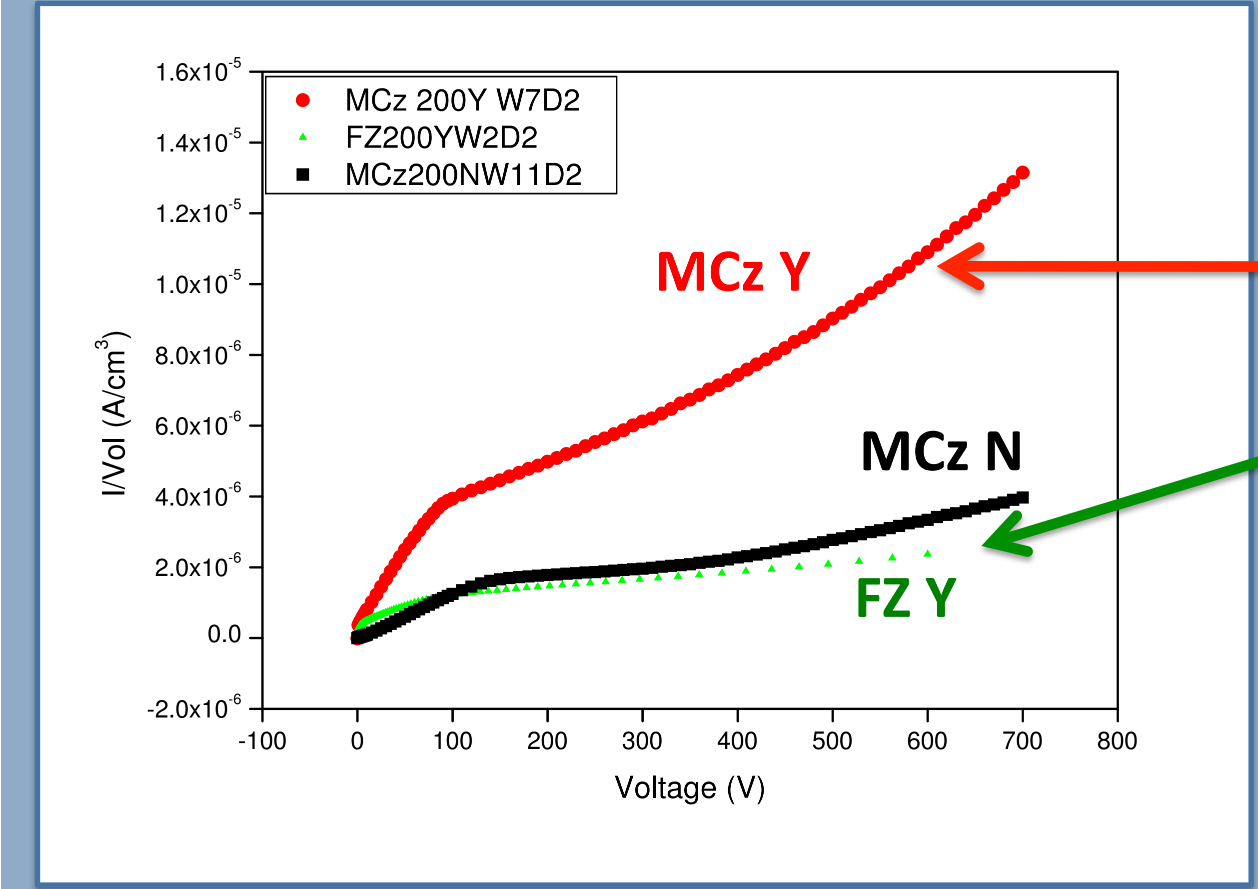
→ High concentration at front side

Strange offset below 220K

→ Recombination?

Some electron traps with impact on N_{eff}

Influence of current generator H(220K)



Max concentration of H(220K) in:

[MCz200 Y] = 9 x 10^{11} cm^{-3}
→ I/Vol@100 V = 4 x 10^{-6} A cm^{-3}

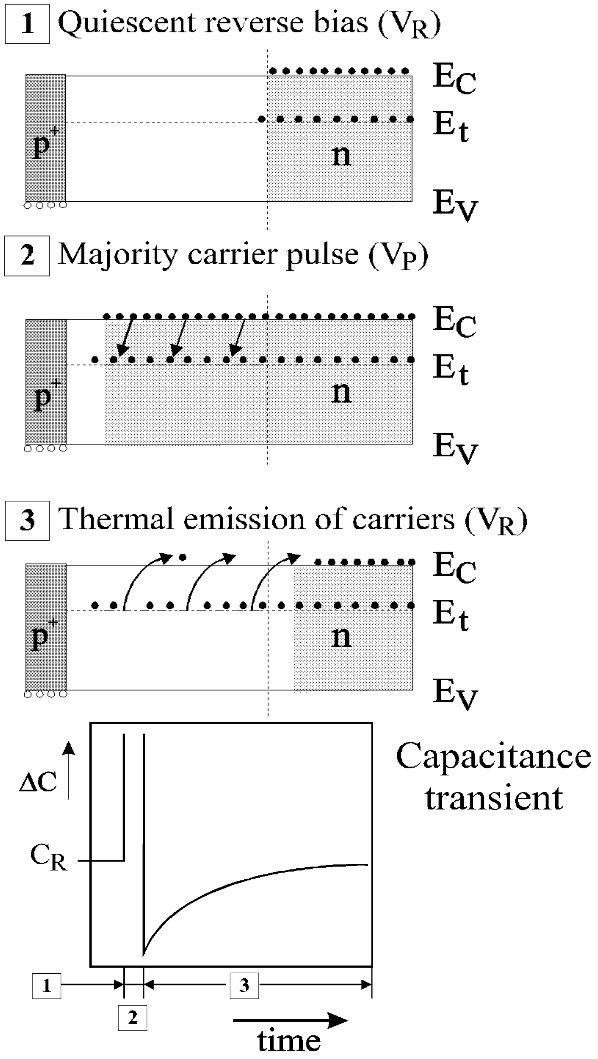
[FZ200 Y] = 3 x 10^{11} cm^{-3}
→ I/Vol@100 V = 1.2 x 10^{-6} A cm^{-3}

Concentrations are qualitatively correct (no guard ring connected)

Current in MCz200 Y higher than MCz200 N and FZ200 Y

Deep Level Transient Spectroscopy

DLTS Principle (electrons)



M. Moll, PhD thesis 1999, Uni Hamburg

Measurement of capacitance transients during T-scan

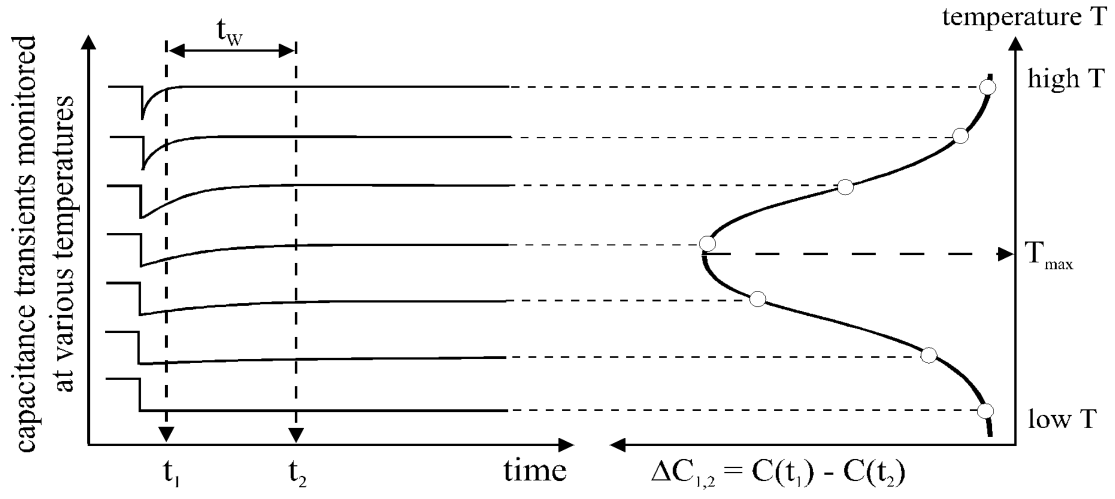
1. Diode in reverse bias
2. Filling of defects with charge carriers during T-scan
3. Emission from defects→ change of capacitance

- Capacitance transient as function of time
- Transient follows:

$$\Delta C = \Delta C_0 \exp(-e_n t)$$

- Analysis of transient concentration:

$$N_t \approx 2 N_D \frac{\Delta C}{C_0}$$



M. Moll, PhD thesis 1999, Uni HH