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# Determination of doping profiles using pad diodes and MOSFETs

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## 12th "Trento" Workshop on Advanced Silicon Radiation Detectors
## FBK Trento
## Feb. 20-23, 2017

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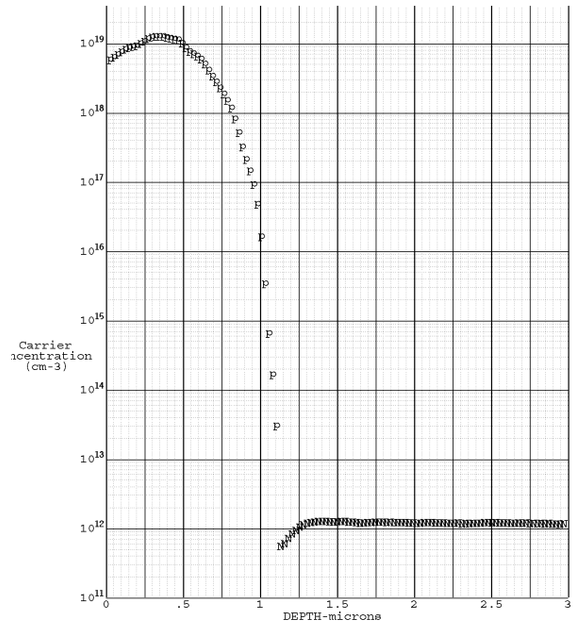
# OUTLINE

1. Introduction
2. Determination of doping profiles using pad diodes
3. Determination of doping profiles using MOSFETs
4. Summary and conclusions

# INTRODUCTION

## Doping profiles:

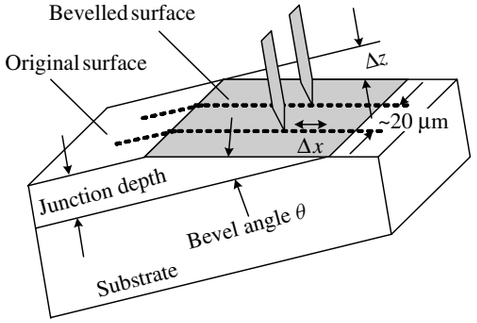
- Are essential for the understanding of the performance of sensors
- Profiles for $n^+$-, $p^+$-implants, p-spray, p-stop and bulk are required
- Manufacturers (usually) do not communicate process details




➡ **Back-engineering is needed to get this information**

## A standard problem, also in electronics → many methods are available

- Destructive: Spreading Resistance, SIMS,...
- Non-destructive: C-V, IV-MOSFET, Rutherford Backscattering, ...



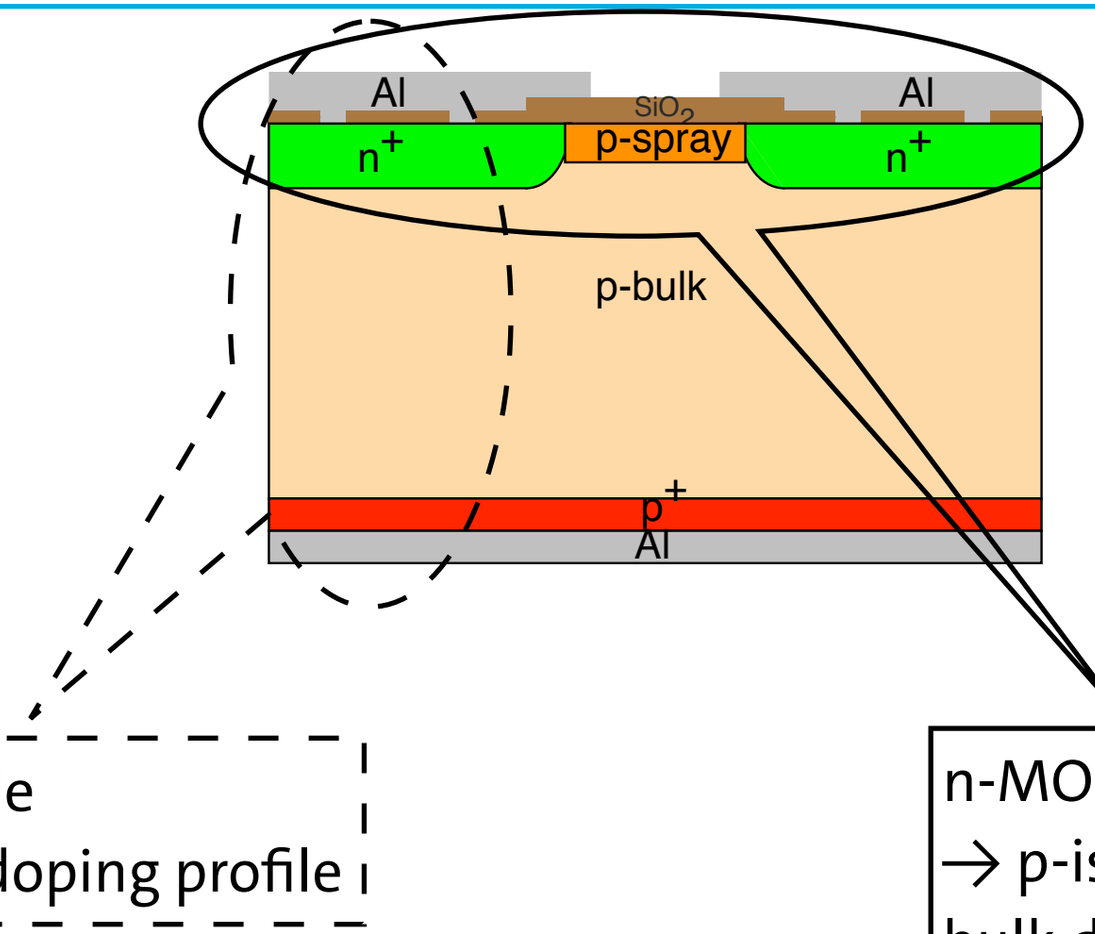

## Wanted:

- Reliable non-destructive precise methods which can be easily performed in a lab

➡ **I-V, C-V based methods**

# INTRODUCTION

## Strip or pixel senors:




## Suitable test structure:

Pad diode
→ bulk doping profile

n-MOSFET
→ p-isolation and bulk doping profile

**In the following I will look into two questions:**

1. How to determine precise doping profiles from C-V on pad diodes?
2. How to determine the p-spray doping profile from I-V on n-MOSFETs?

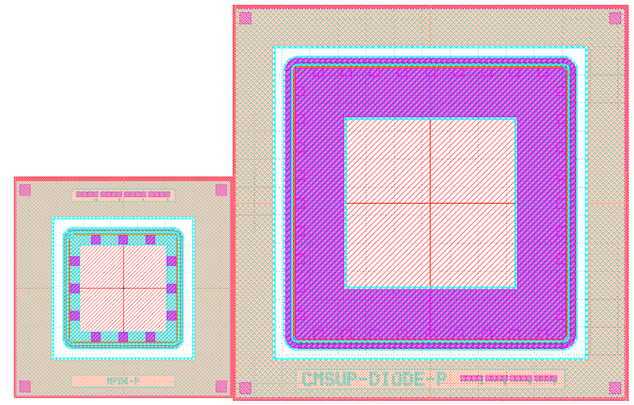
# PAD DIODES

## Standard procedure:

- Pad with GR grounded → C-V a good way to determine doping
- Uniform doping → 1/C²-intercept = built-in voltage $V_{bi} = \frac{k_B T}{q_0} \ln \frac{N_A N_D}{n_i^2}$

## But:

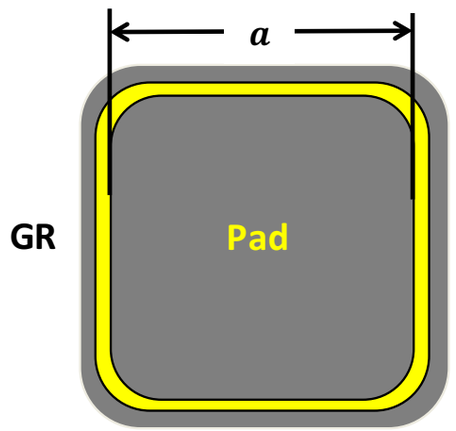
- How big are edge effects?
- What is their influence on the doping determination?




## Simple method:

- 2 squared pad diodes with side length $a_S$, $a_l$
- Assume: $C = a^2 \cdot C_{planar} + 4a \cdot C_{edge}$

→ $C_{planar} = \frac{\frac{C_{as}}{a_s} - \frac{C_{as}}{a_s}}{a_s - a_l}$ and $C_{edge} = \frac{\frac{a_l}{a_s} C_{as} - \frac{a_s}{a_s} C_{al}}{4(a_l - a_s)}$

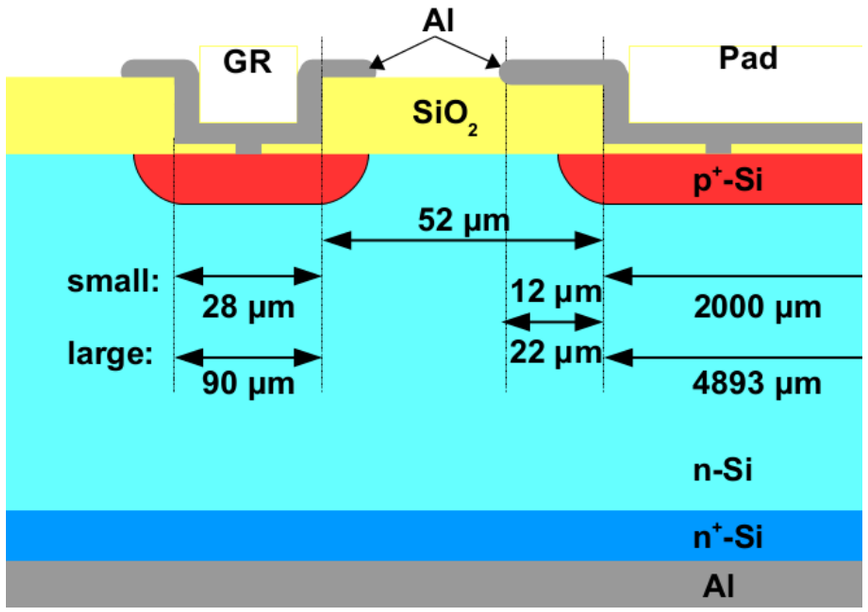


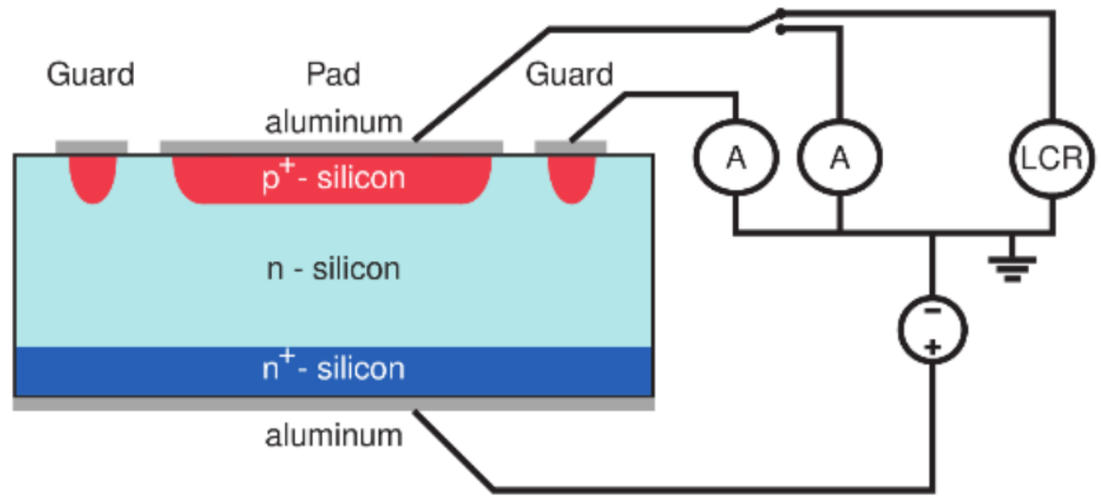

- **Measure** $C_{as}(V)$ **and** $C_{al}(V)$
  Note: $C_{planar}$ (V) [F/cm²] and $C_{edge}$(V) [F/cm]

# PAD DIODES AND MEASUREMENTS

## Test structures + measurement set-up:

- Two sets of 2 pad diodes with guard rings, n-type FZ-Si produces by HPK
- Set 1) Active thickness = 196± 5 µm
- Set 2) Active thickness ≈ 300 µm



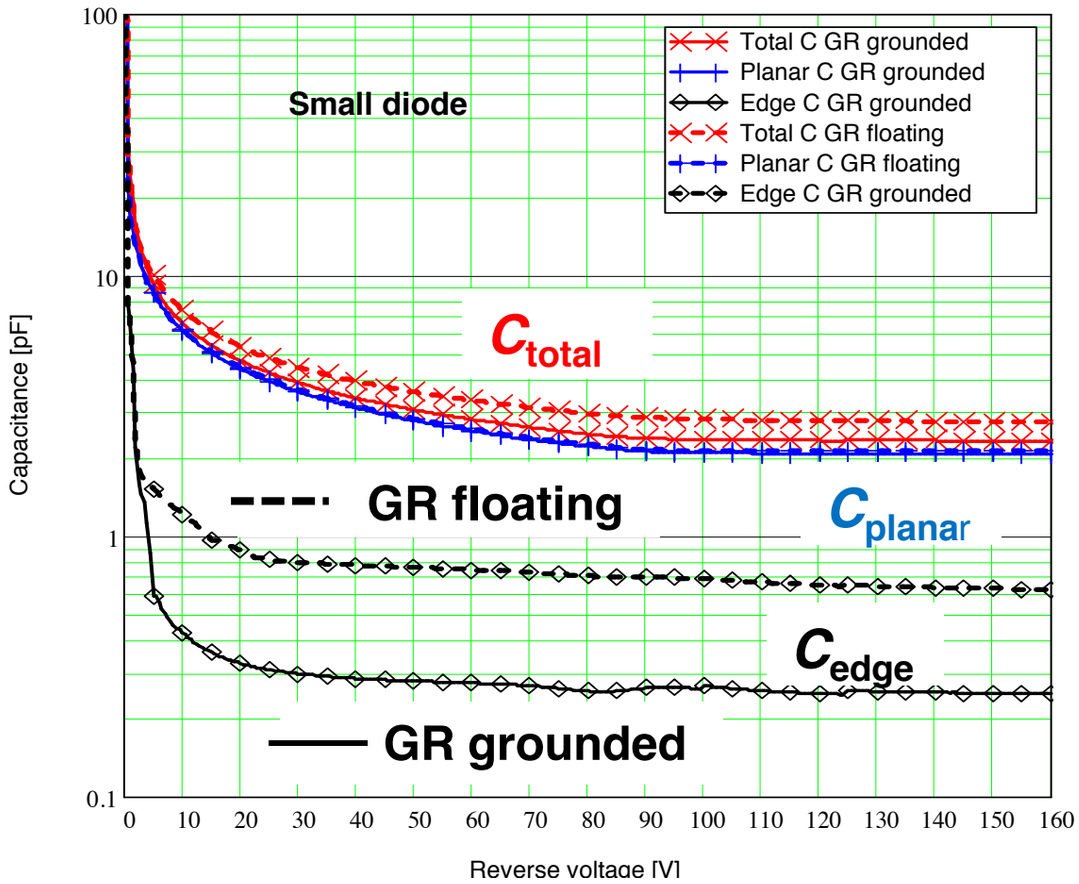



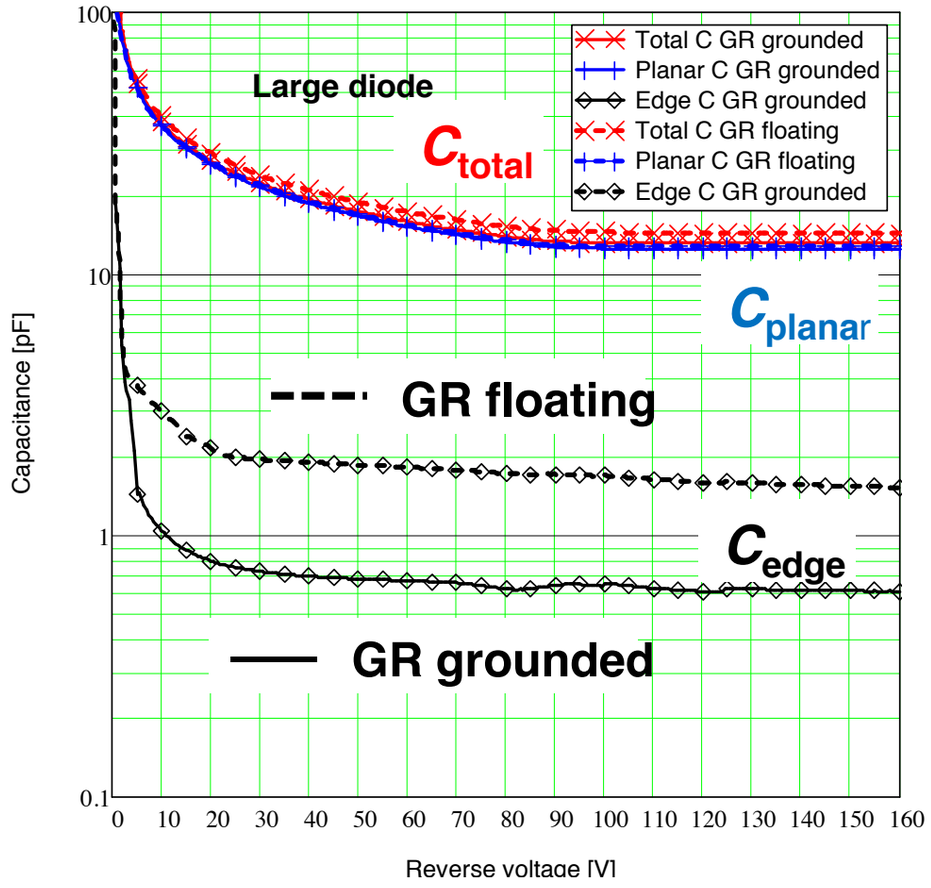

- C-V measurements for GR grounded/floating @20°C, $V_{AC}$ = 500 mV f = 10 kHz [after verifying contact by I-V, $C_{parallel} = C_{series}$; results do not depend on f (200 Hz -200 kHz) and $V_{AC}$ (50 - 500 mV)]
- For a precision measurement the exact knowledge of sensor dimensions, the verification of calibration, and the study of the sensitivity to LCR settings are essential!

# RESULTS: PLANAR + EDGE CAPACITANCE

## $C_{total}$, $C_{planar}$ and $C_{edge}$ with GR grounded and floating (196 µm thick diodes):

arXiv:1605.00778




## Edge correction works well:

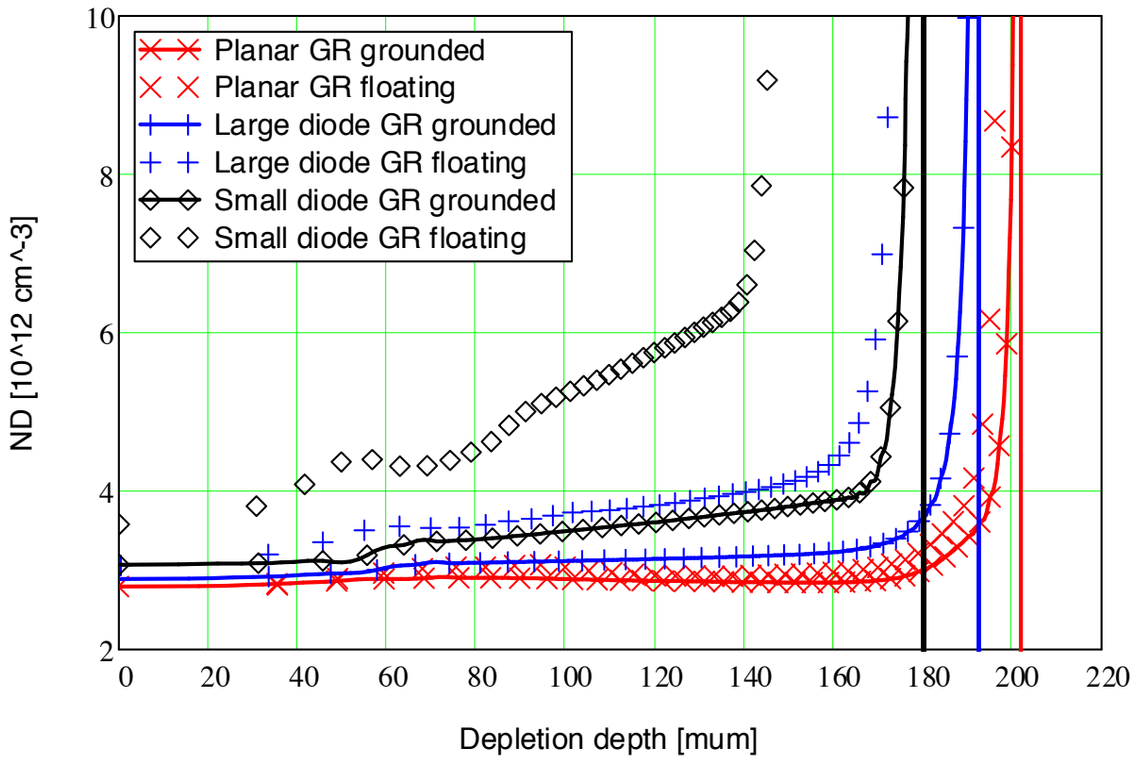
- $C_{planar}$ (GR grounded) ~$C_{planar}$ (GR floating)
- Contribution of $C_{edge}$ to $C_{total}$ (for GR grounded): ~13 % for small, ~3 % for large diode
- $C_{edge}$ (GR grounded)/ $C_{edge}$ (GR floating) = 1/3 → only partial shielding
- $C_{edge}$ and $C_{planar}$ have a different voltage dependence

# DETERMINATION OF $N_D(X)$

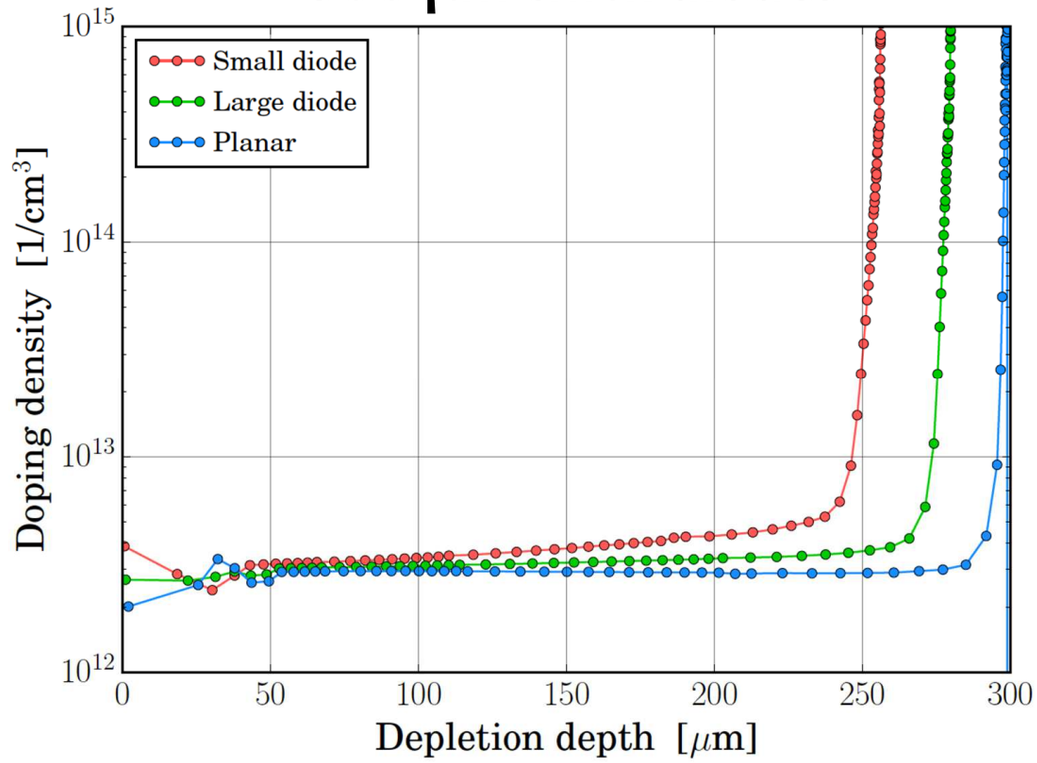
## Influence of edge effects on the d(1/C²)/dV method:

$$x\left(V\right) = \frac{\epsilon_{Si}}{C(V)} \quad \text{and} \quad N_D\left(x\left(V\right)\right) = \frac{2}{q_0 \epsilon_{Si}} \Big/ \frac{d\left(1/C^2\right)}{dV}$$

### 196 µm thick diodes




### 300 µm thick diodes



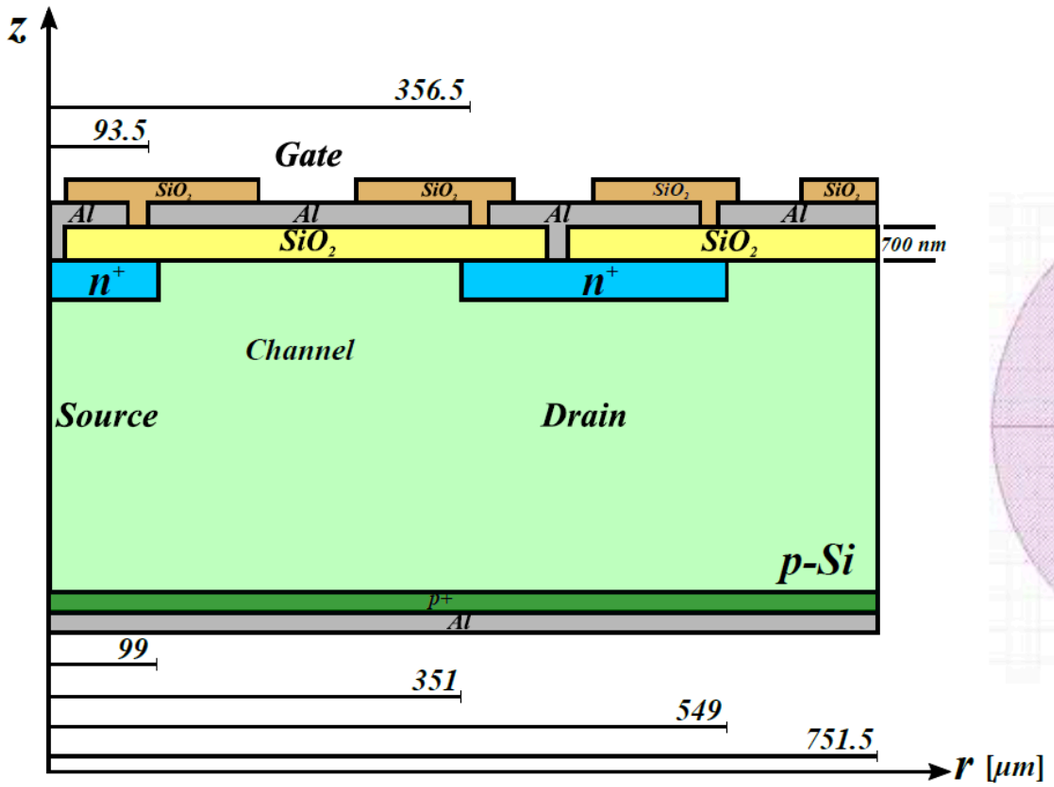

- Only “planar = with edge correction” shows the expected $N_D(x)$ = const (<± 1.5 %) and thickness
- Large GR grounded → ± 5 % deviation from const
- Small GR grounded → ± 15 % deviation from const

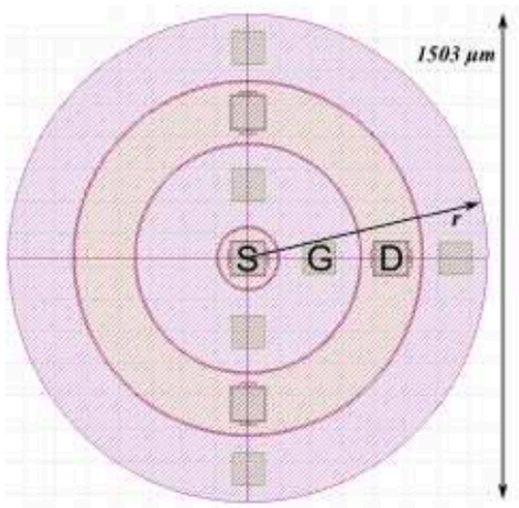
Edge correction required for precise determining the (bulk) doping profile

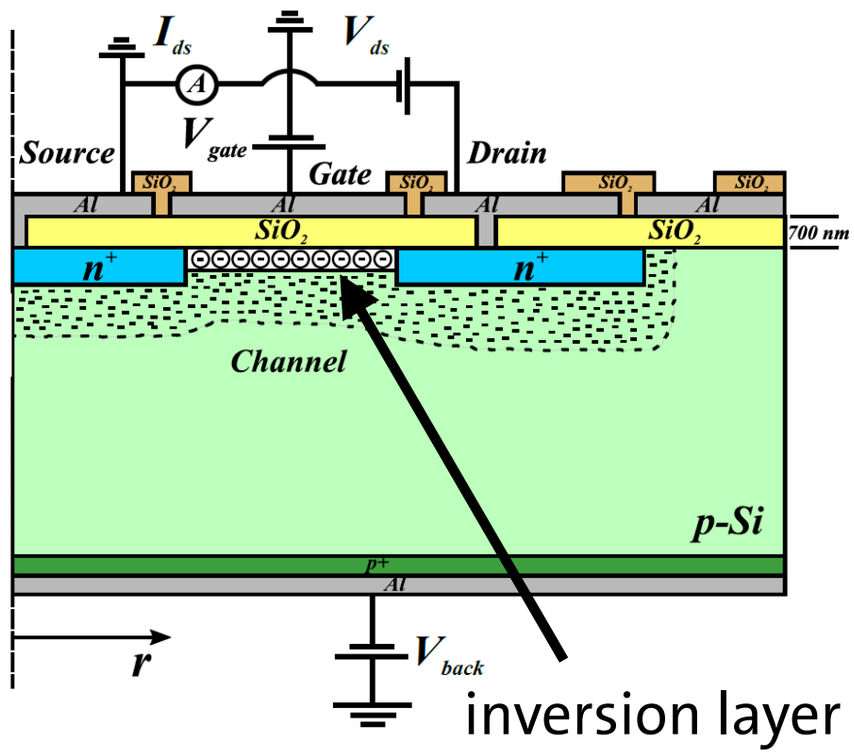
# MOSFETS AND MEASUREMENT SET-UP

## Circular n-MOSFETs produced by HPK on <100> MCz-p-Si:

- Thickness 200 µm
- Bulk doping ≈ $3.3 \cdot 10^{12}$ $cm^{-3}$ (from pad diodes)
- Oxide thickness 700 nm, gate width 252 µm
- MOSFET without p-spray (**M200P**) and with p-spray (**M200Y**)



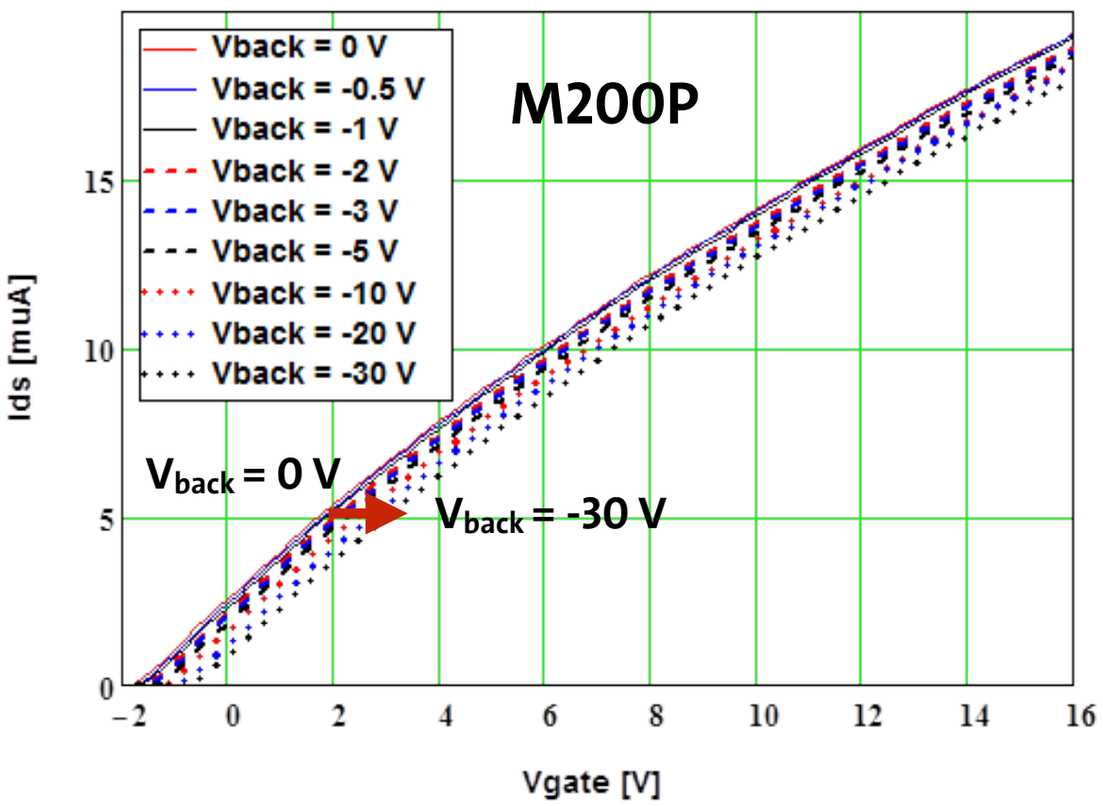



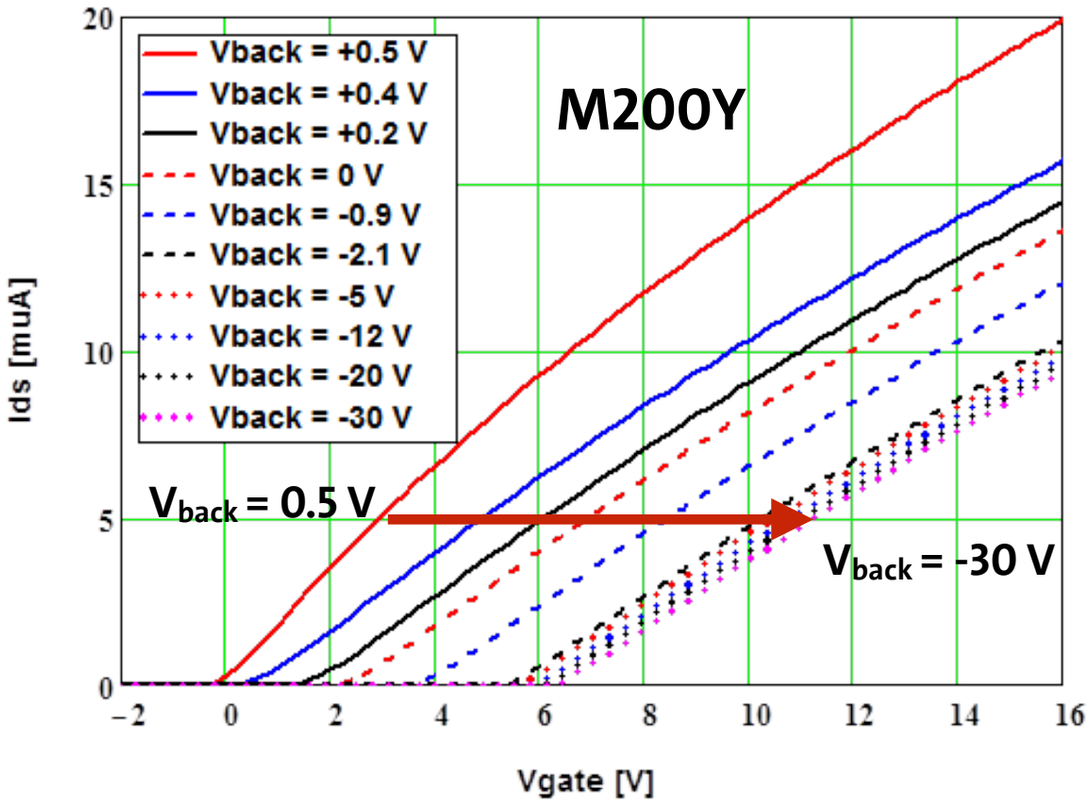

**Measure $I_{ds}$ ($V_{gate}$) for different values of backside voltage $V_{back}$ ( which changes the depletion depth)**

# MEASURED $I_{DS}(V_{GATE})$ CURVES

## Measurements for $V_{gate}$ = -6 … 16 V and $V_{ds}$ = 50 mV (linear region)

- $V_{back}$ = 0 … -30 V for M200P (no p-spray)
- $V_{back}$ = +0.5 … -30 V for M200Y (p-spray)



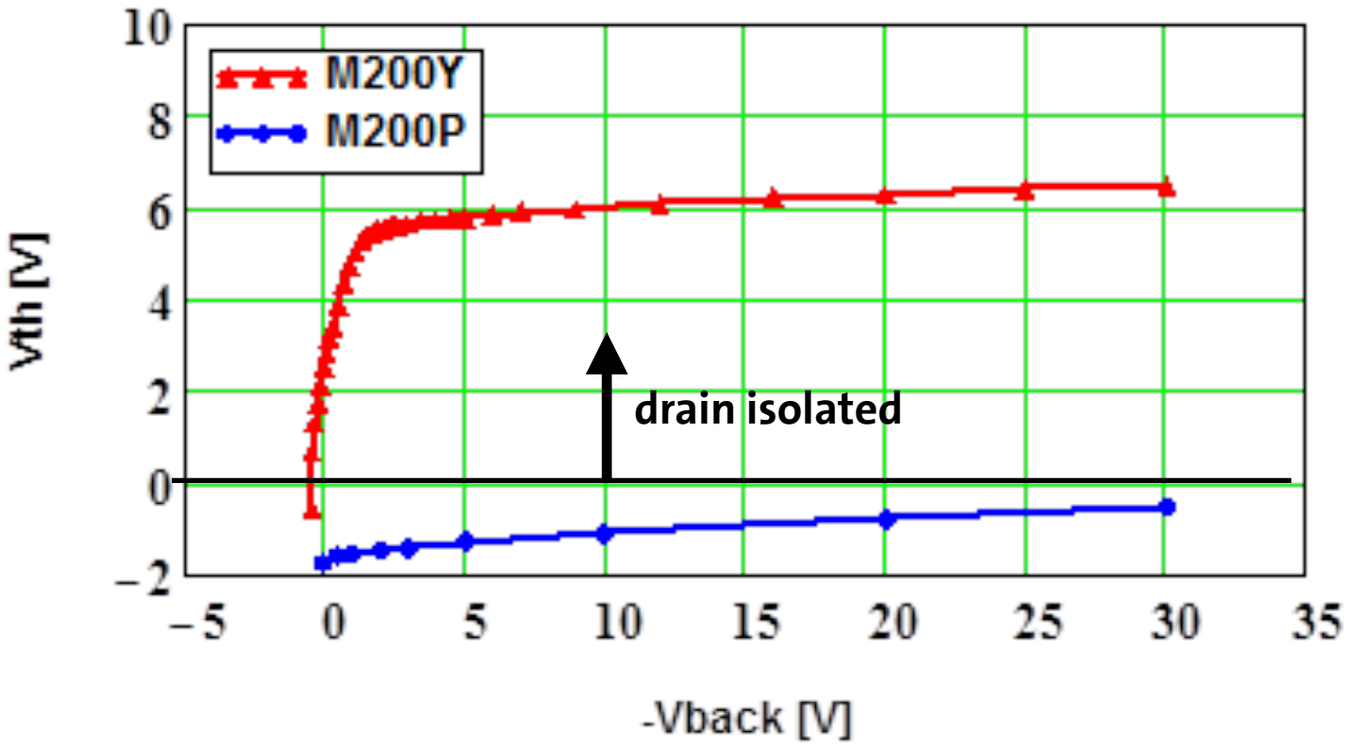




- $I_{ds}$ similar shape, but shift in $V_{gate}$
- Change of $I_{ds}$ with $V_{gate}$ much bigger for MOSFET with p-spray
- Strong dependence on $V_{back}$ → mV precision for $V_{back}$ measurement needed!

# $I_{DS}(V_{GATE})$ FITS VERSUS $V_{BACK}$

## Extract MOSFET parameters:

- n-MOSFET in the linear region: $I_{ds} \approx \frac{W}{L} \cdot \mu_e \cdot C_{ox} \cdot (V_{gate} - V_{th}) \cdot V_{ds}$
- Electron mobility at interface: $\mu_e = \mu_0 \frac{1}{1+(V_{gate}-V_{th})/V_{1/2}}$
- MOSFET width/length: $\frac{W}{L} = 2\pi/ln(r_2/r_1) = 4.964$ and $C_{ox} = \epsilon_{ox}/t_{ox} = 4.933\ \mathrm{nF/cm^2}$




**For $V_{gate} > V_{th}$ + ~3 V model describes data within ~0.1 % for M200Y and 0.5 % for M200P**

- M200P: $V_{th} < 0$ for $-V_{back} < 30$ V → "source -drain shorted"
- M200Y: $V_{th} > 0$ for $-V_{back} > 0$ V → "source -drain isolated"
- M200Y: Large changes of $V_{th}$ for small $V_{back}$ → doping profile

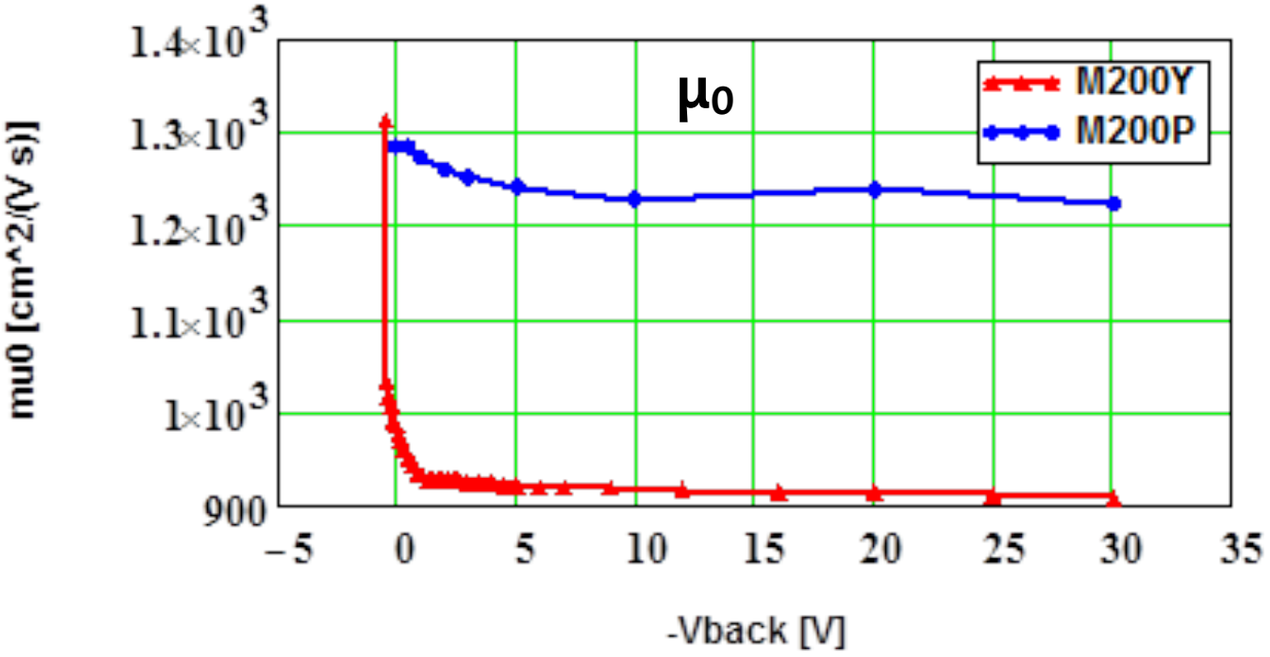
# FIT RESULTS FOR MOBILITY

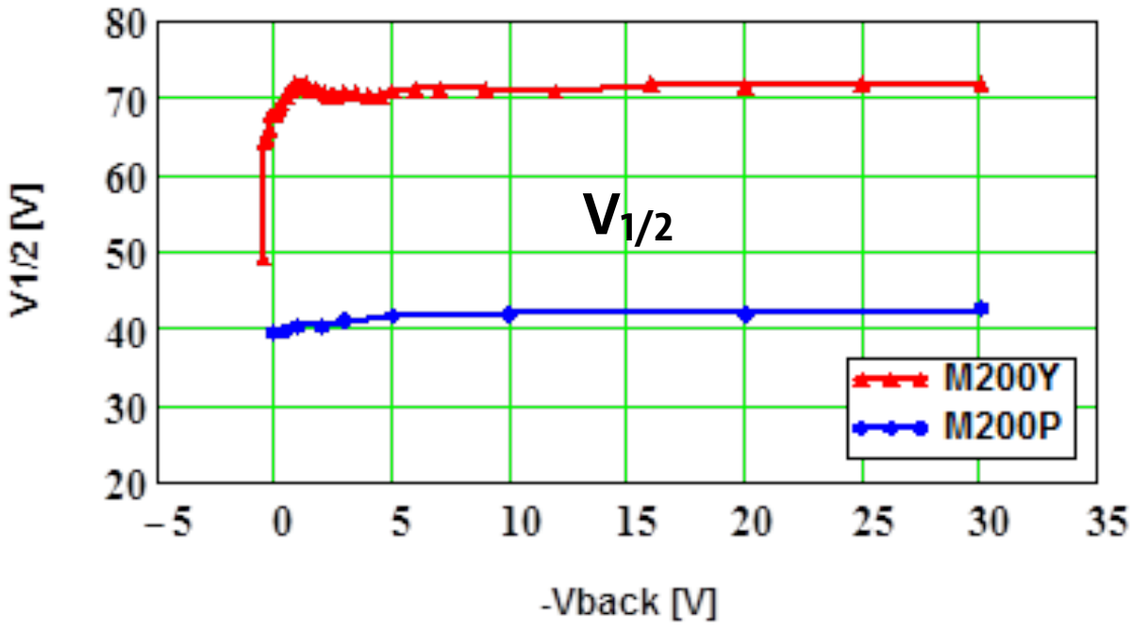
## Mobility parametrisation:

$$\mu_e(V_{back}, V_{gate}) = \mu_0 \frac{1}{1+(V_{gate}-V_{th})/V_{1/2}}$$

- $\mu_0$ electron mobility at the Si-$SiO_2$ for $V_{gate} = V_{back}$
- $V_{1/2}$ voltage at which $\mu_e$ has decreased by a factor 2

Electron mobility at 20°C in the bulk: $\mu_e$ = 1500 $cm^2$ / (Vs)




## Differences in mobility behaviour:

- M200P dominated by surface effects
- M200Y for high $V_{back}$ dominated by doping-density effects

# MOSFET DOPING PROFILING I

## Assumption:

- 1-dim depletion approximation

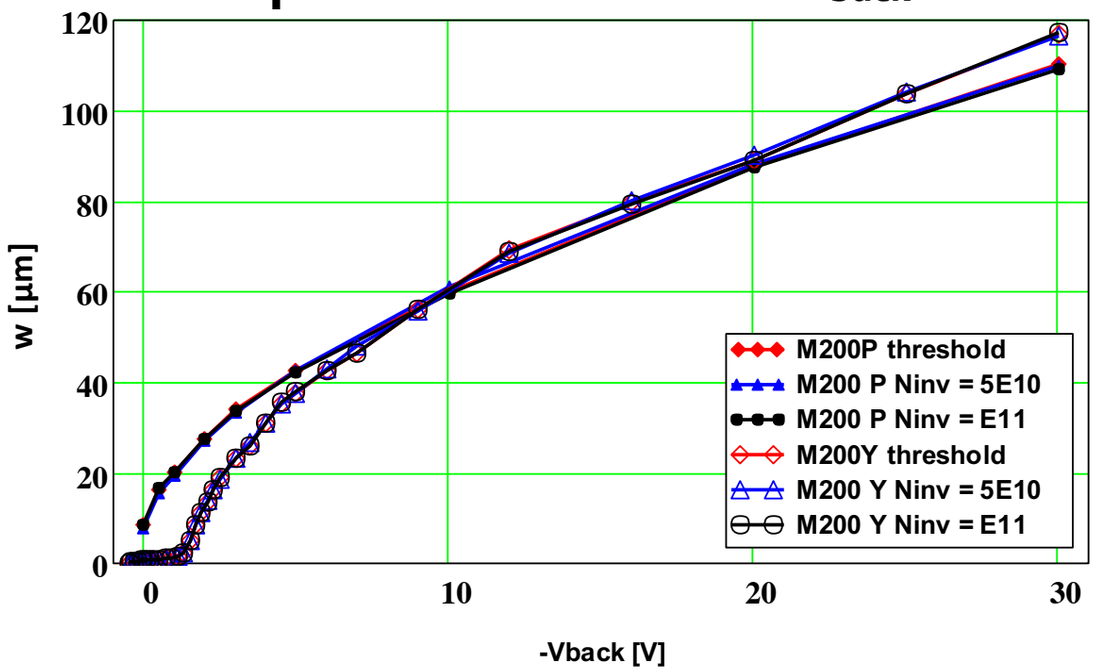
M. Buehler, Appl. Phys. Let. 31(1977) 848-850,
J. M. Shannon, Solid-State Electr. 14(1971) 1099-1106

➡ $x = \frac{\epsilon_{Si}}{C_{ox}} \cdot \frac{\mathrm{d}V_{back}}{\mathrm{d}V_{gate}}$ and $p(x) = \frac{C_{ox}^2}{q_0 \cdot \epsilon_{Si}} \cdot \left( \frac{\mathrm{d}^2 V_{back}}{\mathrm{d}V_{gate}^2} \right)^{-1}$

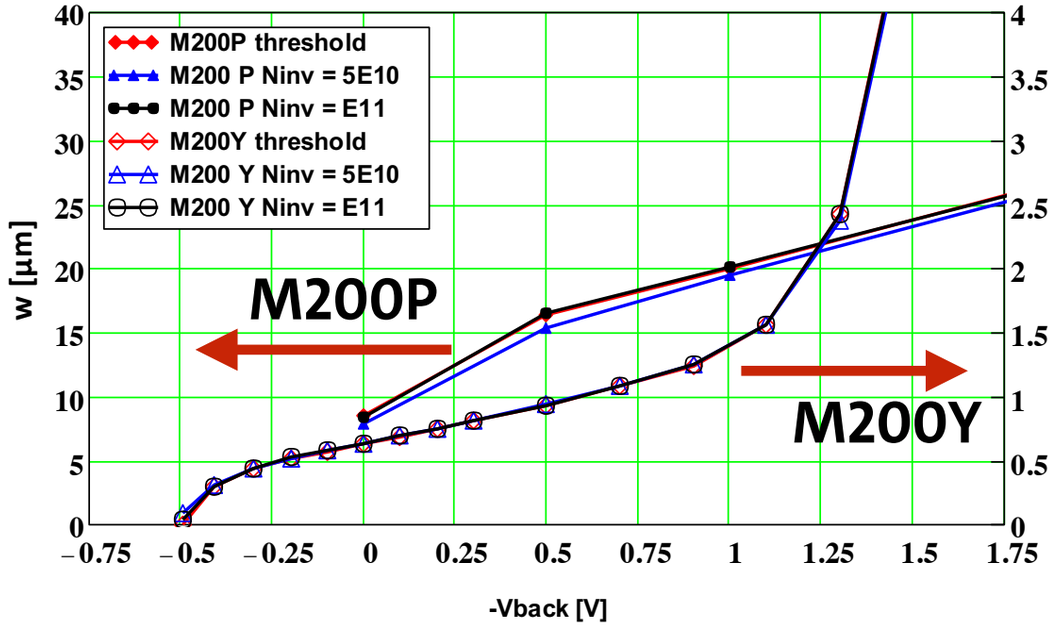
x = w($V_{back}$,$N_{inv}$) depletion depth
p(x) majority-charge carrier density
$N_{inv}$ inversion charge density

**$V_{gate}$ is obtained by interpolating $I_{ds}(V_{gate},V_{back})$ for a given $N_{inv}$ using** $N_{inv} = \frac{L}{q_0 W} \cdot \frac{I_{ds}(V_{gate},V_{back})}{\mu_e(V_{gate},V_{back})}$

**Depletion width w vs $V_{back}$**




**Depletion width w vs $V_{back}$**




- For M200P approx. square root dependence of w(|$V_{back}$|) (uniform doping)
- For M200Y the change of w($V_{back}$) for small values of -$V_{back}$ is much weaker (p-spray)

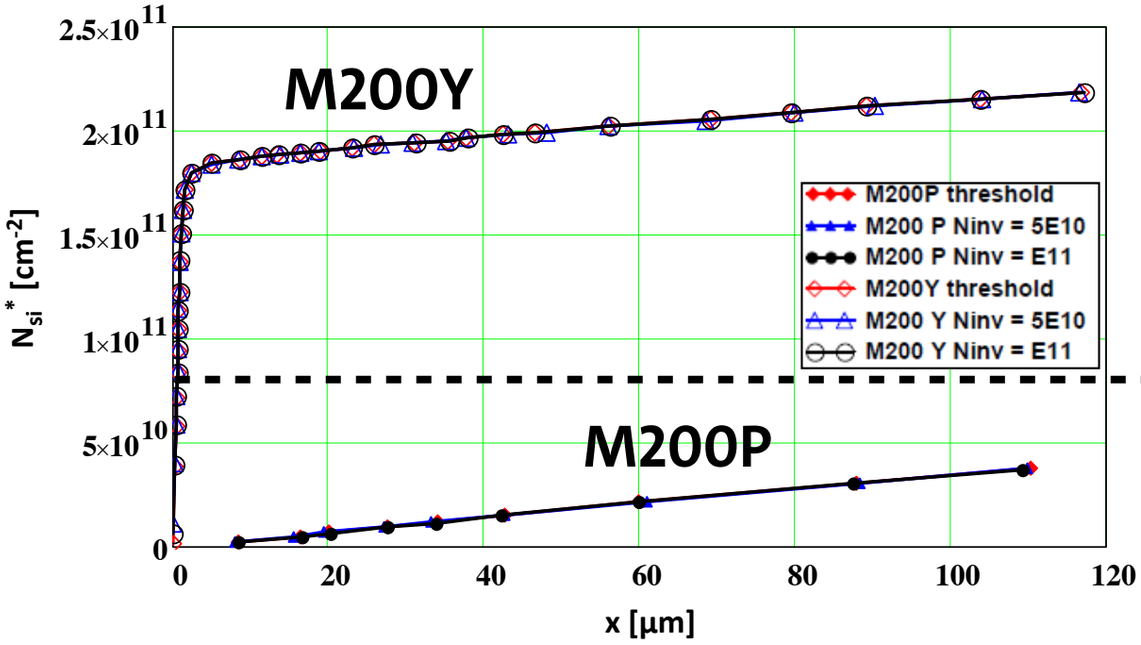
# MOSFET DOPING PROFILING II

## Integral of dopant density $N^*_{Si}$ follows from charge neutrality for the entire MOSFET

$$\int_{x_0}^{x} p\left(x\right)\ \mathrm{dx} = \frac{C_{ox}}{q_0} \cdot \left(V_{gate}\left(x\right) - V_{gate}\left(x_0\right)\right) \approx N^*_{Si}\left(x, x_0\right)$$

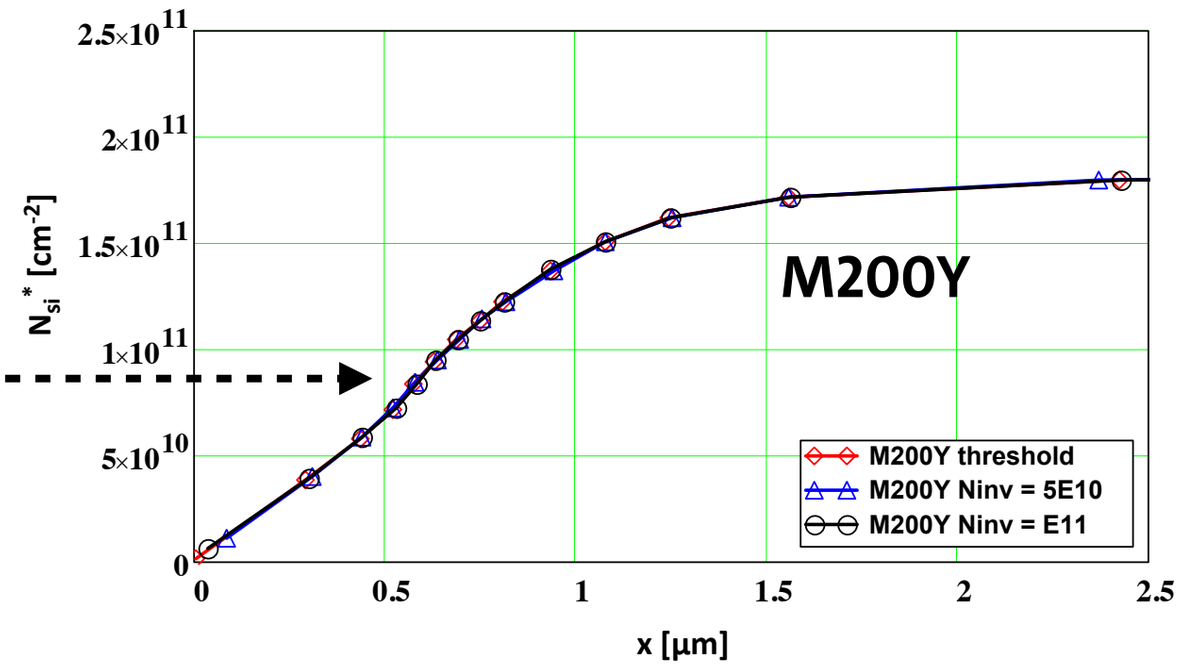
Units in [$cm^{-2}$]

### Dopant density $N^*_{Si}$ as function of x




Zoom

### Dopant density $N^*_{Si}$ as function of x




- $N^*_{Si}$ is independent of $N_{inv}$ (check of method)
- For x > 10 µm the slope of $N_{Si}(x)$ is approx. the same for M200Y and M200P

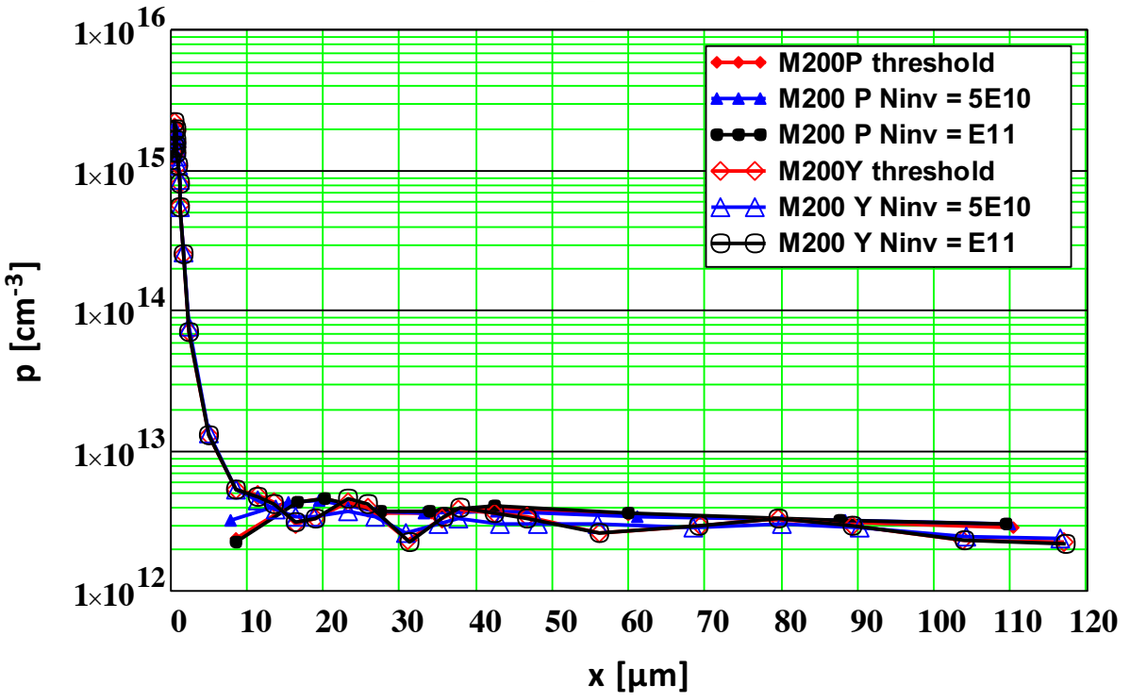
➡ M200Y and M200P have the same constant bulk doping

# MOSFET DOPING PROFILING III

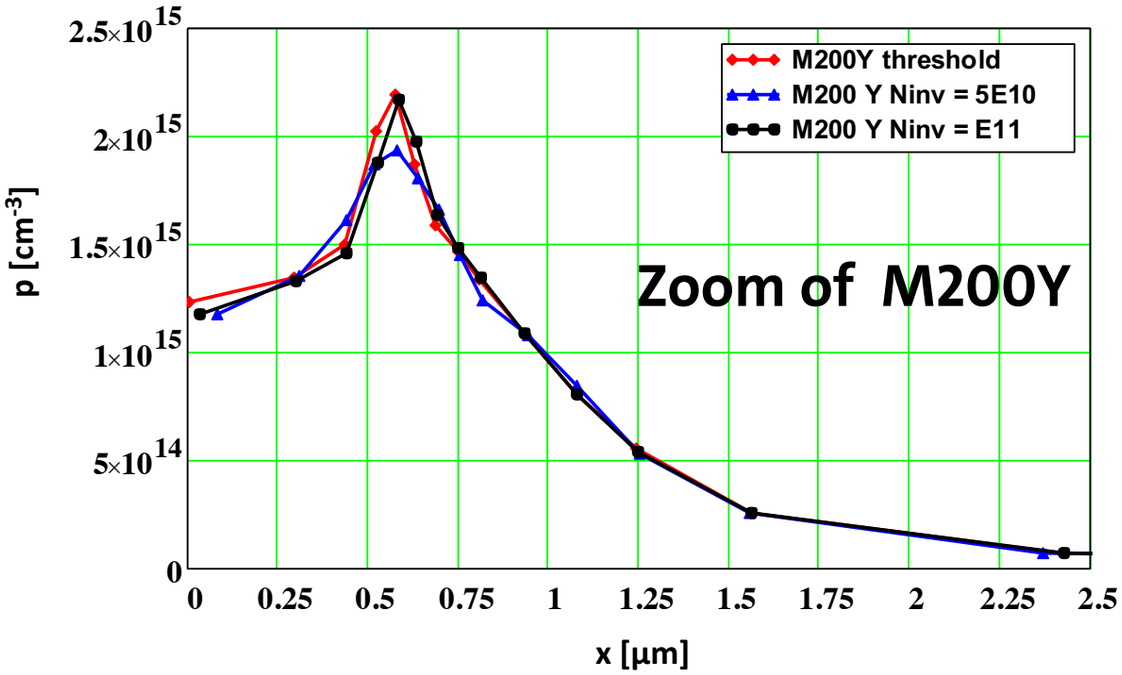
## Estimate the density of free charge carriers p(x):

- Differentiate integral of p(x) with respect to x

### Carrier density p as function of x




### Carrier density p as function of x




- Same constant bulk doping of M200P and M200Y for x > 10 µm
- p(x) around maximum very sensitive to exact values of $V_{back}$ ,

➡Integral $N^*_{Si}$ seems to be reliable determination, p(x) can only be considered as an estimate

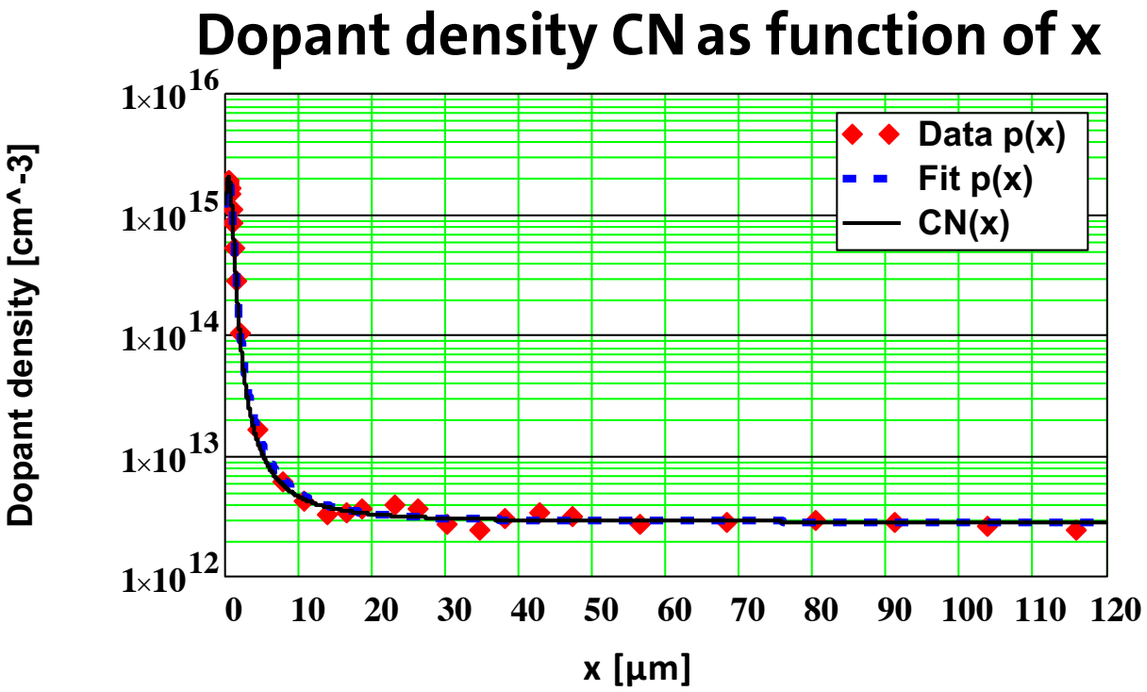
# MOSFET DOPING PROFILING IV

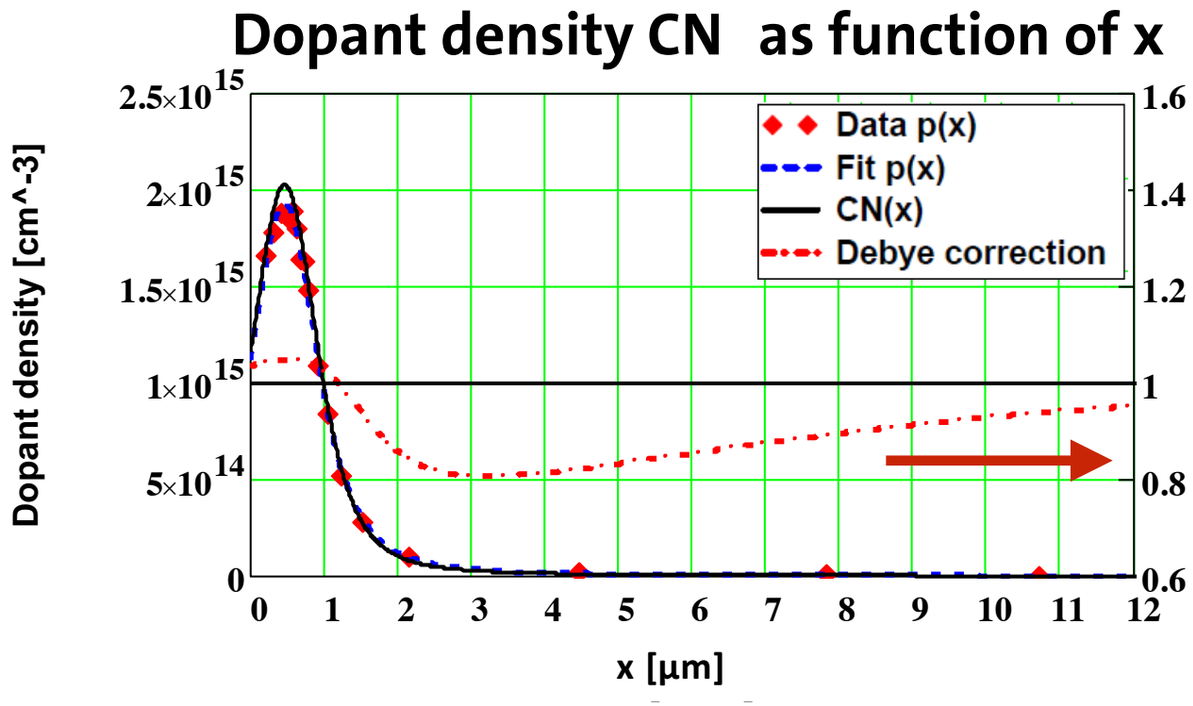
## Doping profile for TCAD simulations:

- Smooth p(x) and fit to phenomenological function

$$p(x) = A \cdot \exp\left(\frac{-(x-\mu)^2}{2\cdot\left(\sigma_0^2+\sigma_1^2\cdot(x-\mu)^2\right)}\right) + B$$

Units in [cm$^{-3}$]




- The function only approximately describes the observed p(x) dependence
- Best description for low $N_{inv}$
- Debye correction, $CN(x) = p(x) - \frac{\epsilon_{Si}\cdot k_B\cdot T}{q_0^2}\cdot\frac{\mathrm{d}^2\ln(p(x))}{\mathrm{d}x^2}$ , amounts to +5 % at maximum p(x), and to -20 % at x = 3 µm
- Within measurement accuracy Debye correction is a small effect

# SUMMARY AND CONCLUSIONS

## Edge effects in Si-pad diodes must corrected to:

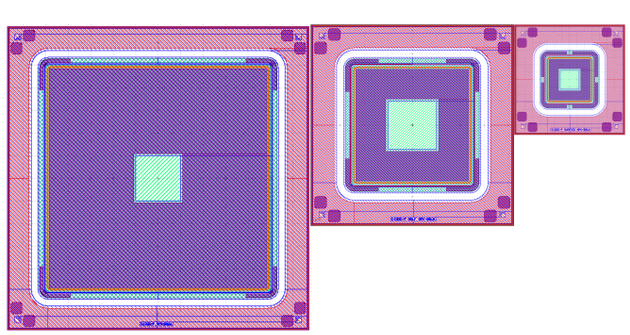
- Obtain precise bulk doping profile
- Use measurement to compare (or as input) for 1D TCAD simulations

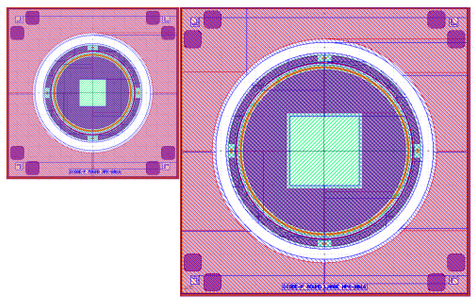
## Circular nMOSFETs can be used for the determination of the p-spray doping profile:

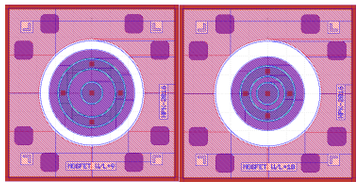
- The methods is non-destructive and simple to implement (check of method with TCAD simulations are under way)
- Integrals of the doping density can be accurately determined
- To provide input to TCAD doping profiles are parameterised by a phenomenological function

## Take home message:

- Implement pad diodes of different sizes with identical guard ring designs as standard test structure
- Use nMOSFETs for the determination of the p-isolation + surface effects







## Thank you for your attention!!!

# Backup