Edge effects in Si-pad diodes and their influence on doping profile determinations

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Outline:

- Introduction and method
- Pad diodes investigated and measurements
- Results:
  a) contribution of C_{edge} to $C_{pad\ diode}$
  b) Active thickness
  c) Built-in voltage
  d) Different methods for doping density determination
  e) Models for C_{edge}
- Summary and conclusions

Introduction and Method

Standard procedure:

- Pad sensors with GR grounded → C-V a good way to determine doping
- Uniform doping → $1/C^2$-intercept = built-in voltage ($-2k_BT/q$)

Is this correct?

- How big are the edge effects?
- Can we understand them?
- What is their influence on the doping determination?

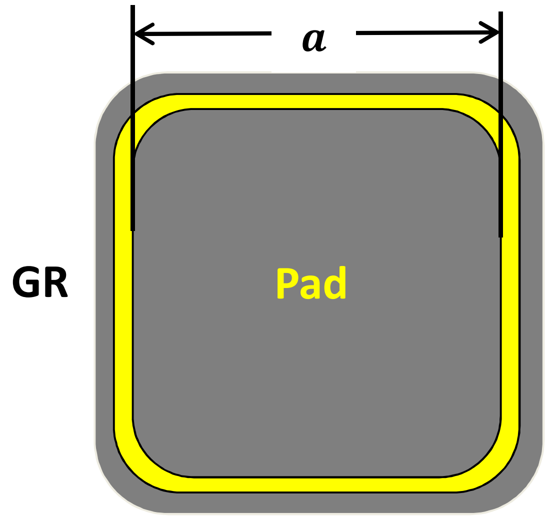
Method:

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

$$\rightarrow \quad C_{planar} = \frac{\frac{C_{aS}}{aS} - \frac{C_{aL}}{aL}}{a_S - a_L}, \quad C_{edge} = \frac{\frac{a_L}{a_S} C_{aS} - \frac{a_S}{a_L} C_{aL}}{4(a_L - a_S)}$$

- Measure $C_{aS}(V)$ and $C_{aL}(V)$

  Note: $C_{planar}(V)$ [F/cm²] and $C_{edge}(V)$ [F/cm]

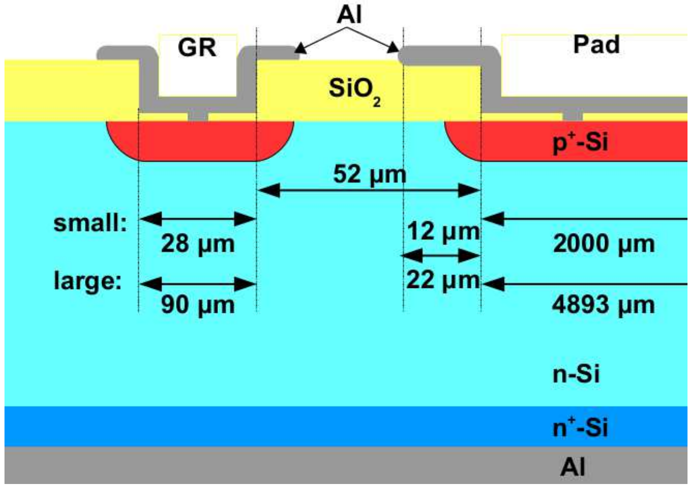


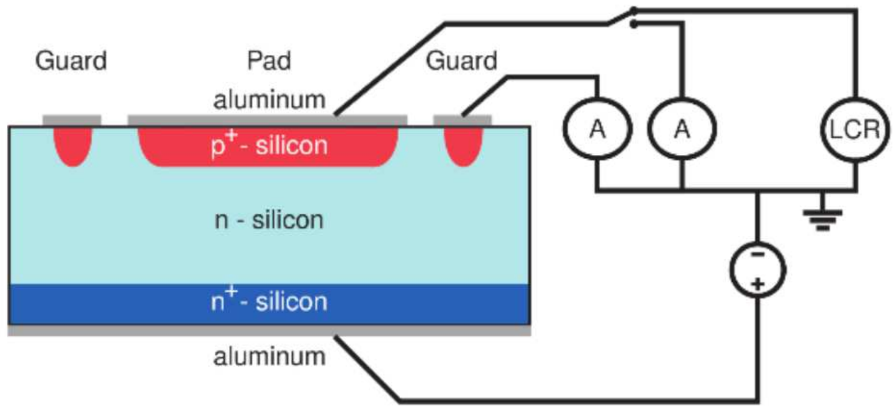
Use different methods to determine the doping profile $N_D(x)$ from $C_{planar}(V)$, $C_{aS}(V)$ and $C_{aL}(V)$

Pad diodes and measurements

Test structures and measurement set-up:

- **2 pad diodes with guard rings, n-type FZ-Si, produced by Hamamatsu HPK**
- **Active thickness = 196 ± 5 µm**





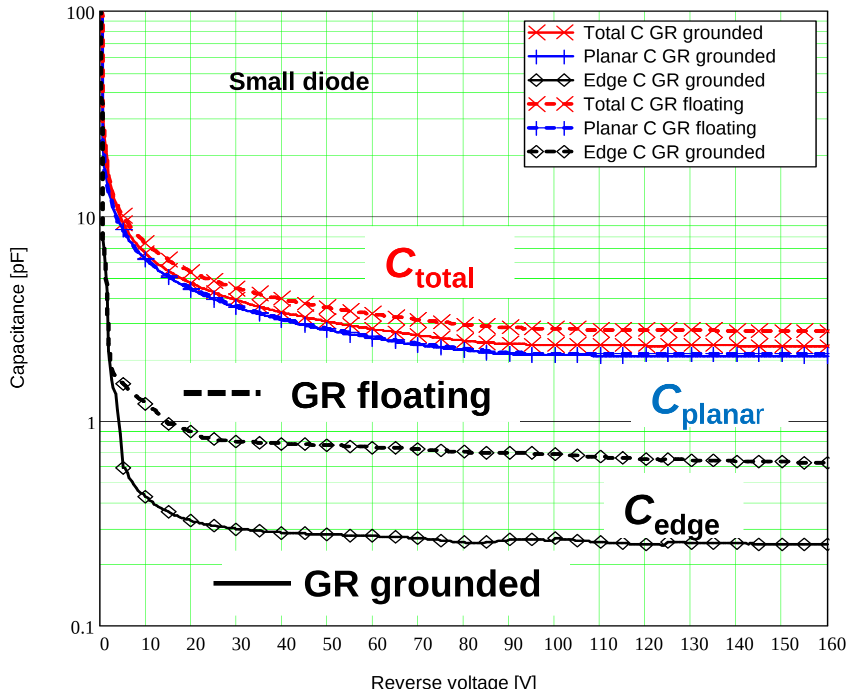
- **C-V measurements for GR grounded/floating @20°C, V_{AC} = 500 mV, f = 10 kHz [after verifying contact by I-V, $C_{parallel}$ = C_{series}; results do not depend on f (200 Hz – 200 kHz) and V_{AC} (50 – 500 mV)]**

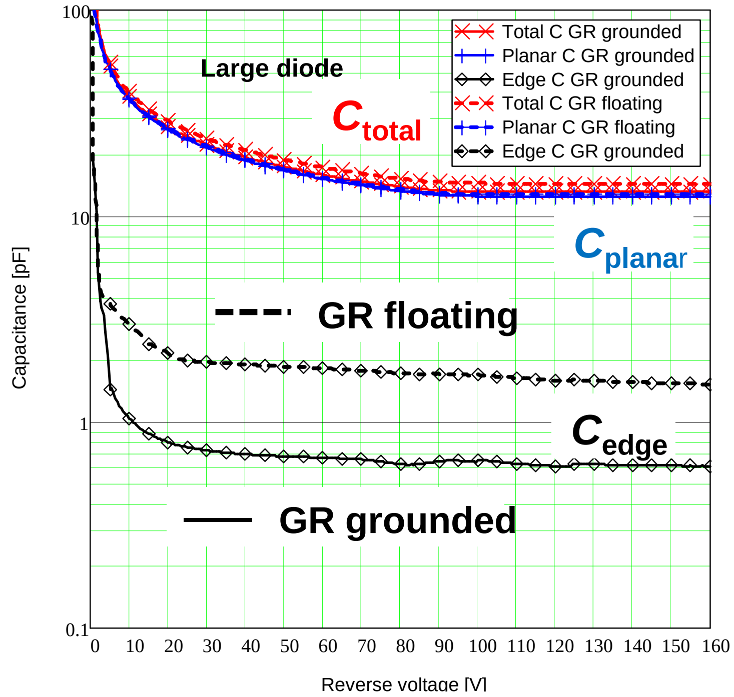
For a precision measurement

the exact knowledge of sensor dimensions, the verification of the calibration, and the study of the sensitivity to LCR settings are essential !

Results: Planar and edge capacitance

C_{total}, C_{planar} and C_{edge} with GR grounded and floating:





Edge correction works well: C_{planar}(GR grounded) ≈ C_{planar}(GR floating)

Contribution of C_{edge} to C_{total}: ~13% for small, ~ 4% for large diode for GR grounded

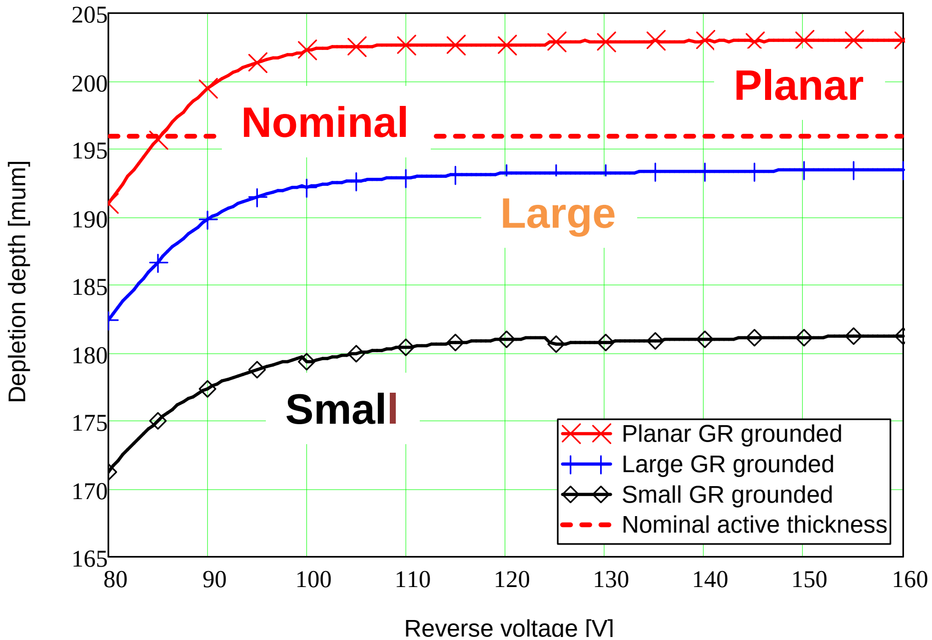
C_{edge} (GR-grounded)/C_{edge} (GR-floating) ≈ 1/3 → only partial shielding

C_{edge} and C_{planar} have a different voltage dependence

→ How does C_{edge} influence the doping determination ?

Nominal thickness

Depletion depth $w(V) = \frac{\varepsilon_{Si}}{C(V)}$ → $V > V_{dep}$ → **nominal thickness**



Estimation of nominal thickness

mech. thickness	**204 ± 3 µm**
- 1 x passivation	**- 0.5 ± 0 µm**
- 2 x aluminum	**- 3.5 ± 1 µm**
- 2 x implants	**- 4 ± 1 µm**
nom. thickness	**196 ± 5 µm**

Planar: Δ (expected – extracted active thickness) = -7 ± 3 µm →barely compatible !

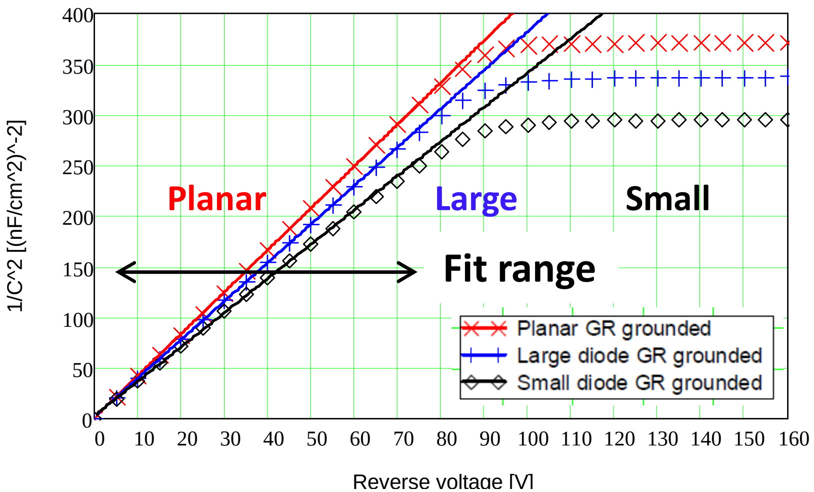
Large: Δ (expected – extracted active thickness) = +3 ± 3 µm → in agreement

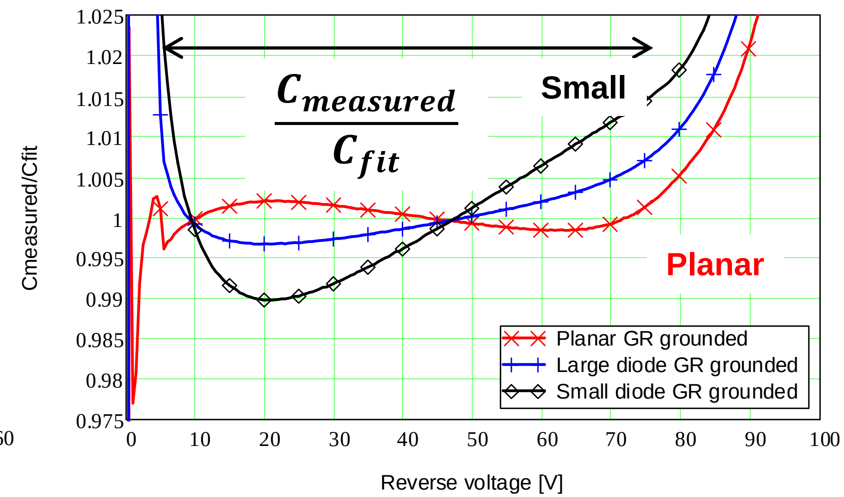
Small: Δ (expected – extracted active thickness) = +14 ± 3 µm → significant deviation !!

Determination of $\langle N_D \rangle$: $1/C^2$ method

Study influence of edge effects on N_D (doping dens.) determination
→ compare different standard and non-standard methods

$1/C^2$ method: $N_D = \dfrac{2}{\varepsilon_{Si}\, q_0\, b}$ with $\dfrac{1}{C^2} = b\,(V + V_0);\ V_0 \approx V_{bi}$ **(built-in voltage)**





Fit for V = 5 – 75 V
(„error“ ΔC = 0.1% C)

	N_D [cm^{-3}]	V_0 [mV]	χ^2 /NDF
Planar	2.86 10^{12}	240	250/139
Large	3.12 10^{12}	520	1300/139
Small	3.50 10^{12}	910	9600/139

Fit only reasonable for planar; fit degrades if no edge correction (EC)
“wrong N_D values“ if no EC, even for GR grounded, size dependence!

Slope and intercept $1/C^2$ → doping + built-in voltage

Y.F. Chang, “The capacitance of p-n junctions”, *Solid-State Electronics Vol.10, 1967, 281*

The p-n junction capacitance is nearly a square root function of the voltage, in agreement with the Schottky theory. However, the capacitance method cannot be used to determine the junction barrier height.

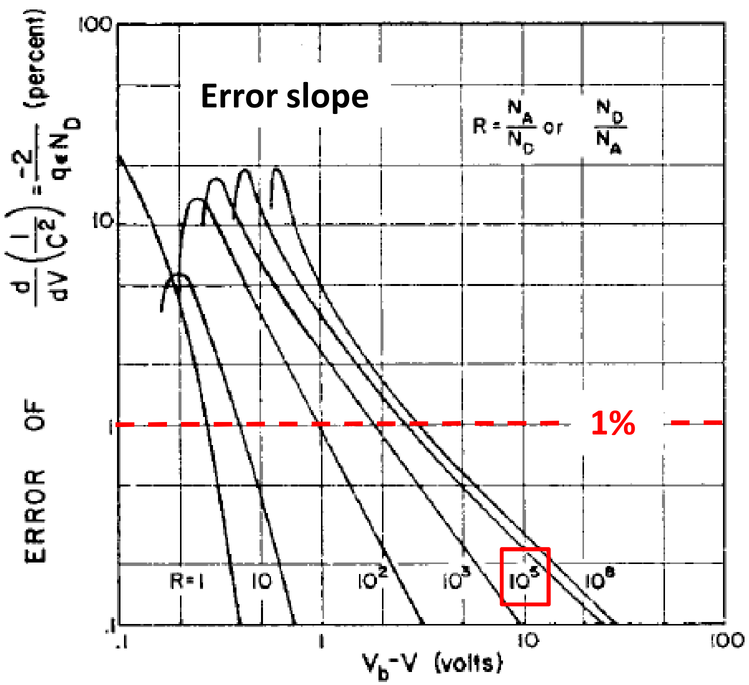


FIG. 6. The error in the Schottky slope of $1/C^2$ vs. voltage.

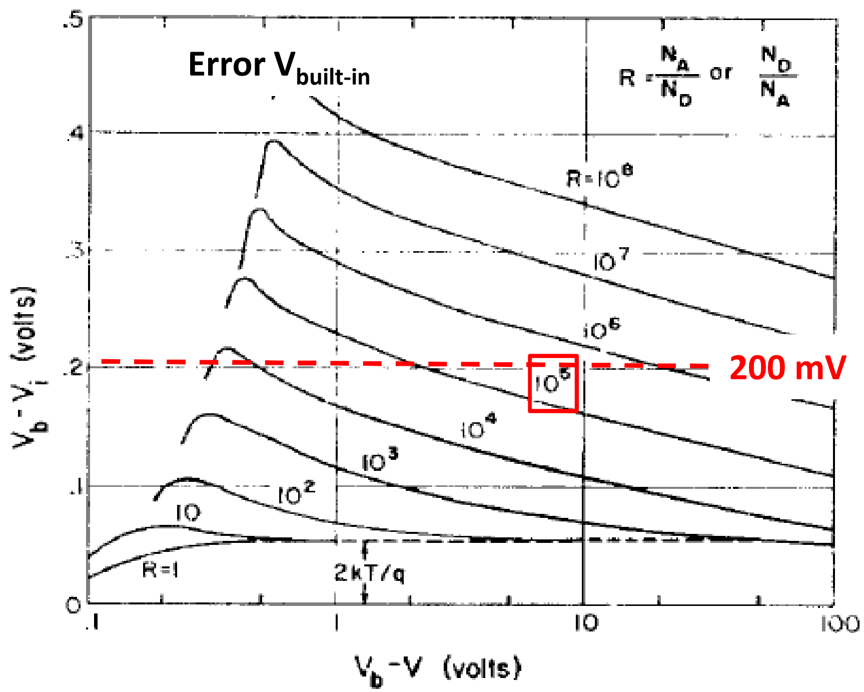


FIG. 7. The difference between barrier voltage (V_b) and $1/C^2$ intercept voltage (V_i).

$1/C^2$ slope good method for N_D determination

V_0 needs major corrections for V_{bi} determination

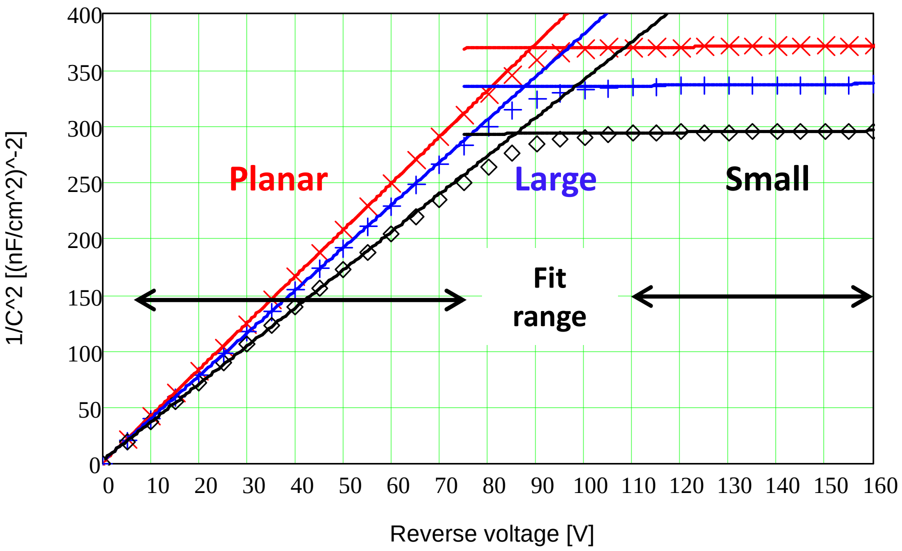
→ V_0 = 250 mV not incompatible with V_{bi} ~ 550 mV

Determination of <N$_D$>: V_{depl} method

V_{depl} method:

Intercept of $1/C^2$ fits below and above the full depletion voltage V_{depl}

$$N_D = \frac{2\,\varepsilon_{Si}}{q_0\, d^2}\, V_{depl} \quad (d = 200\ \mu\text{m sensor thickness})$$



	N_D [cm^{-3}] ($1/C^2$)	N_D [cm^{-3}] (V_{depl})
Planar	$2.86\ 10^{12}$	$2.93\ 10^{12}$
Large	$3.12\ 10^{12}$	$2.88\ 10^{12}$
Small	$3.50\ 10^{12}$	$2.82\ 10^{12}$

N_D values agree for "planar"

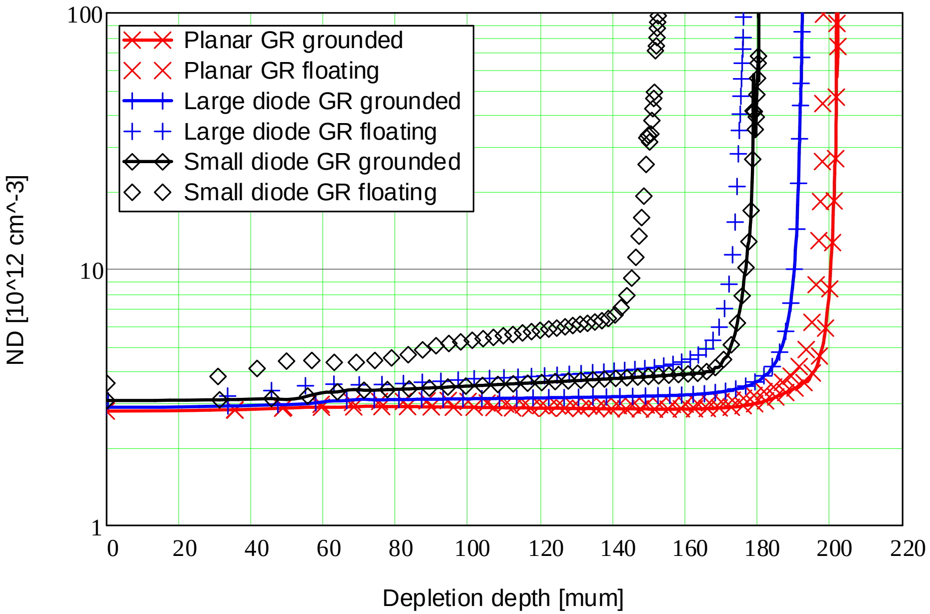
For the large and small diodes changes by -1.7% and -3.8%

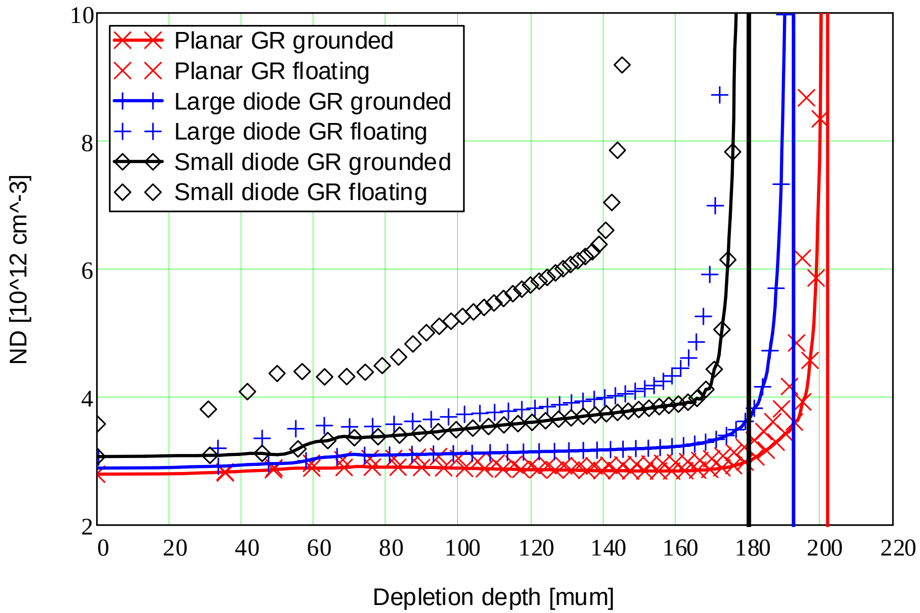
Influence of edge correction smaller than for $1/C^2$ method

(but dependence on fit range!)

Determination of $N_D(x)$: $d(1/C^2)/dV$ method

d(1/C²)/dV method: $x(V) = \frac{\varepsilon_{Si}}{C(V)}$ and $N_D(x(V)) = \frac{2}{q_0 \varepsilon_{Si}} \Big/ \frac{d(1/C^2)}{dV}$





Only "planar = with EC" shows the expected $N_D(x)$ = const (<±1.5%)

Large GR grounded → ≈ 10% increase with x

Small GR grounded → ≈ 25% increase with x

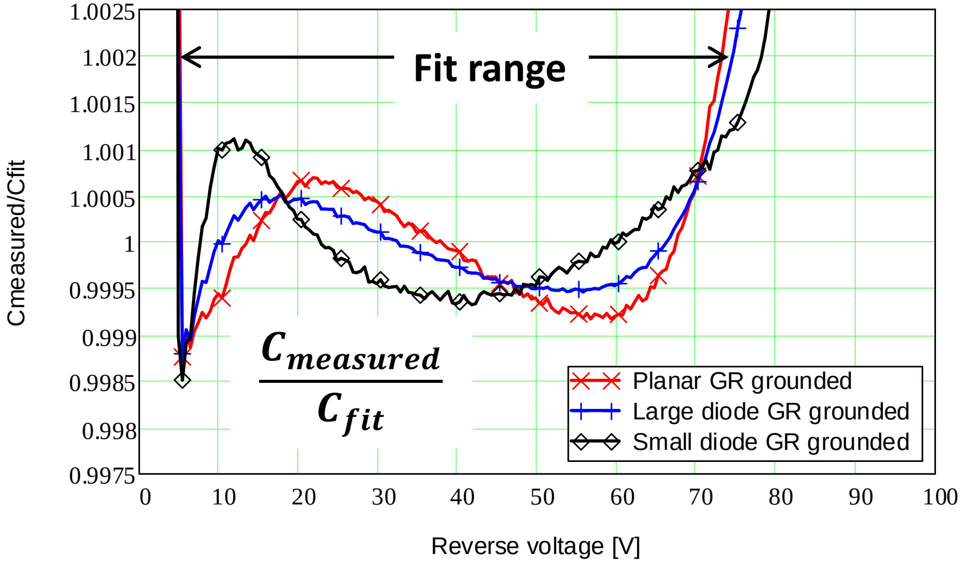
Edge correction is required for determining the doping profile

Determination of $N_D(x)$: C-V fit method

The (novel?) C-V fit method:

$$N_d(x) = \frac{\varepsilon_{Si}}{q_0}\frac{d^2V(x)}{dx^2},\ V(w) = \frac{q_0}{\varepsilon_{Si}}\int_0^w d\xi \int_\xi^w N_D(\xi')d\xi' \quad \text{(w … depletion depth)}$$

$$\rightarrow V(w) = \frac{q_0}{\varepsilon_{Si}} w^2\left(\frac{N_0}{2} + \frac{\alpha\, w}{3}\right) - V_0 \ \text{and}\ V(C) = \frac{q_0 \varepsilon_{Si}}{C^2}\left(\frac{N_0}{2} + \frac{\alpha\, \varepsilon_{Si}}{3\, C}\right) \ \text{for}\ N_D(x) = N_0 + \alpha\, x$$



	N_D [cm^{-3}] ($1/C^2$)	N_D [cm^{-3}] (V_{depl})	$<N_D>$ [cm^{-3}] (C-V)	ΔN_D [cm^{-3}]
Planar	$2.86\ 10^{12}$	$2.93\ 10^{12}$	$2.87\ 10^{12}$	$-0.48\ 10^{11}$
Large	$3.12\ 10^{12}$	$2.88\ 10^{12}$	$3.10\ 10^{12}$	$1{,}59\ 10^{11}$
Small	$3.50\ 10^{12}$	$2.82\ 10^{12}$	$3.49\ 10^{12}$	$5{,}36\ 10^{11}$

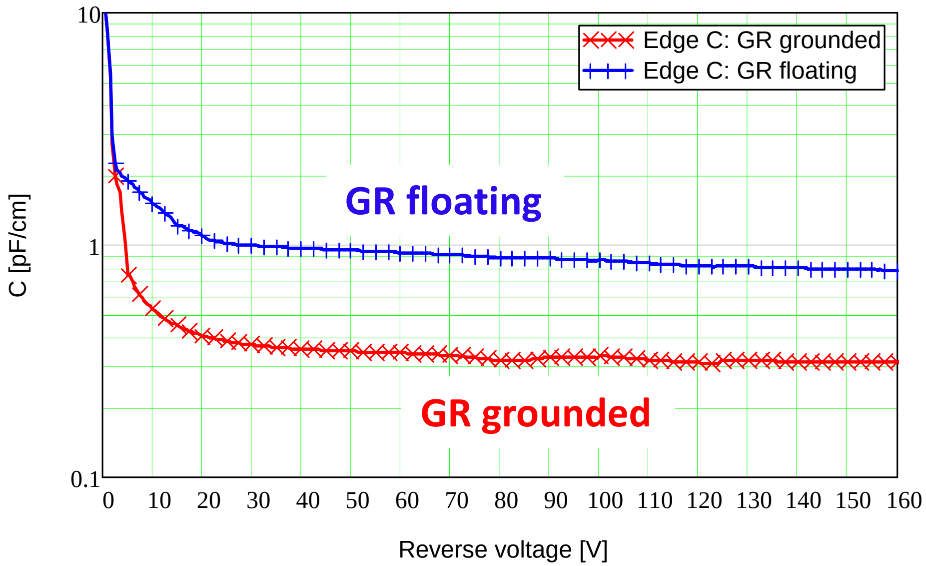
Significant improvement of fit quality compared to $1/C^2$ method

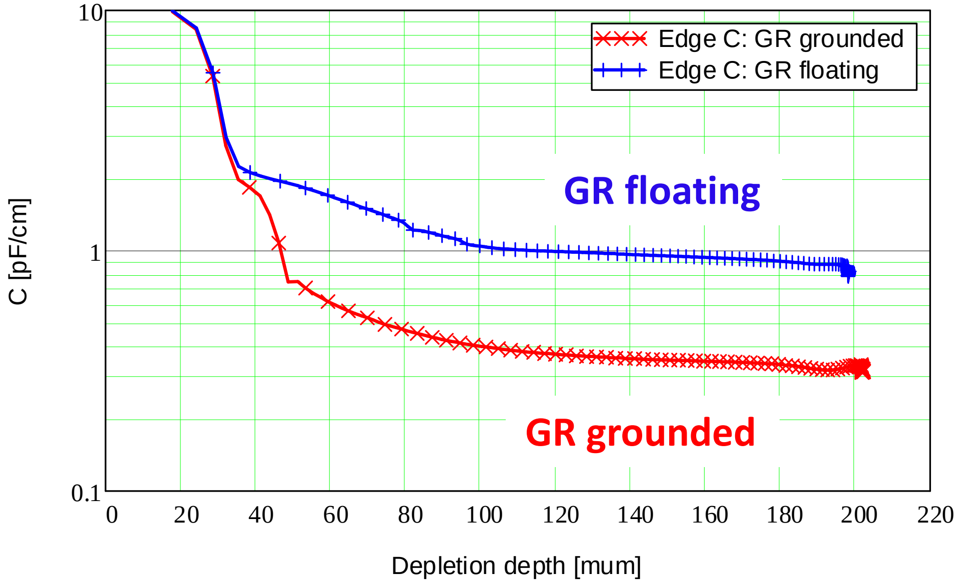
Quantitative confirmation of results from $d(1/C^2)/dV$ method

Edge correction is required for determining the doping profile

Edge capacitance: Model 1

Edge capacitance/cm vs. Reverse voltage vs. w (depletion depth of „planar“)





Model 1: Copeland IEEE Trans.ED17(1970)404 simulation for circular pad diode

→ assume same relation for square diode with same (periphery/area):

$C_{edge} = \pi\, \varepsilon_{Si}\, b/2$ with $b = 1.5$ for Schottky, $b = 0.46$ for mesa-type pn diode

→ expect ~2.5 pF/cm, ~0.76 pF/cm for GR floating, GR grounded independent of V

C_{edge}-ratio (GR grounded) / (GR floating) well described (0.31 expected, 0.36 measured)

Right order of magnitude (data 2.5 below model)

Voltage dependence of data not described

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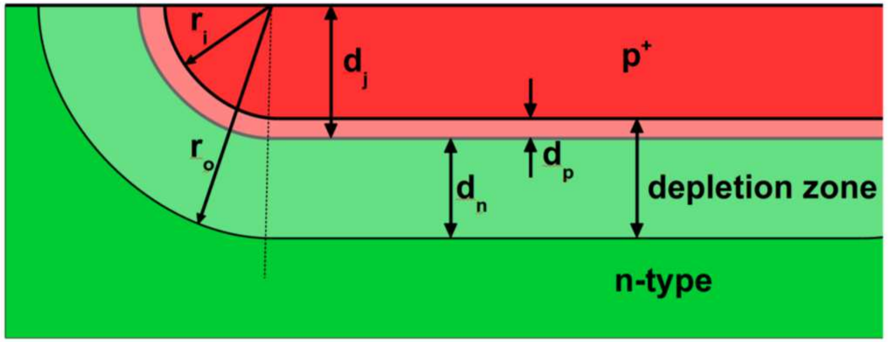
Edge capacitance: Model 2

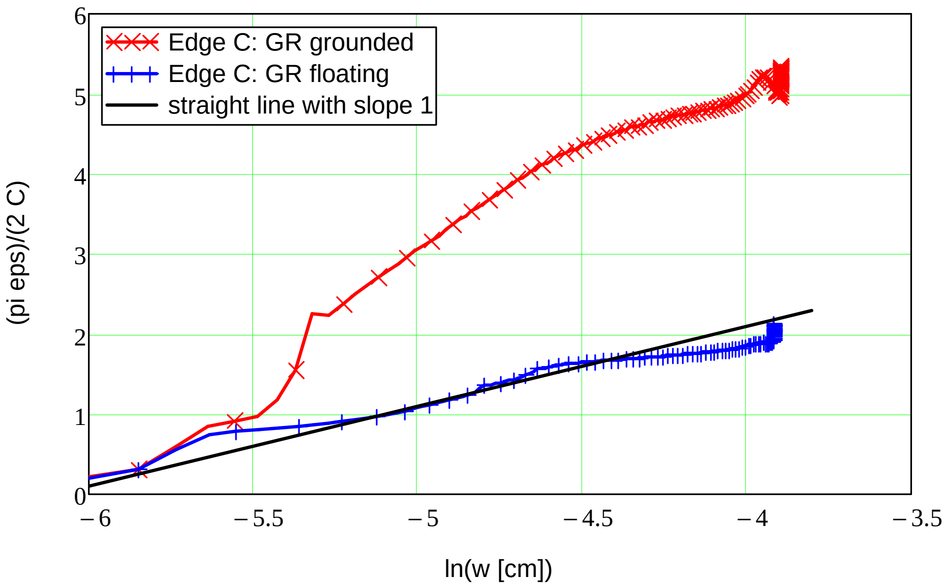
Model for GR floating (RK):

„Cylindrical“ C_{edge}



$$C_{edge} = \frac{2\,\pi\,\varepsilon_{Si}}{\ln(r_o/r_i)}\,\frac{1}{4} \approx \frac{\pi\,\varepsilon_{Si}}{2\,\ln(w/d_j)}$$

$$\Rightarrow \quad \frac{\pi\,\varepsilon_{Si}}{2\,C_{edge}} = \ln(w) - \ln(d_j)$$



→ **Straight line vs ln(w) observed; however d_j = 22 µm, where 2 µm expected**

Voltage dependence of C_{edge} for GR floating well described

Value of observed d_j unphysical

Waiting for Godot + TCAD simulation

Summary and conclusions

- **A straight-forward method to determine the edge contribution to the capacitance for square pad sensors with guard rings has been presented and verified.**
- **Biasing the guard ring to the same potential as the diode reduces the edge capacitance (1/3), but does not eliminate it.**
- **The sensitivity to the edge capacitance of different methods for determining the Si-bulk doping has been investigated:**
  - **For doping profiles a correction for edge effects is required.**
  - **For average doping the „full-depletion voltage method“ ≈ reliable.**
- **Value + voltage dependence of the edge capacitance has been compared to simple models → only qualitative agreement found.**
- **A method of fitting a parametrization of the doping profile to the C-V measurements has been proposed and tested**
  → recommended for doping profile determinations.

It is recommended to implement pad diodes of different sizes with identical guard ring designs as standard test structures

Backup slide

Table1+2

	a [μm]	$C(120\,\mathrm{V})$ [pF/cm^2]	d [μm]	V_d [V]	$N_D^{V_d}$ [10^{12}/cm^3]	N_D^{1/C^2} [10^{12}/cm^3]	V_0 [mV]	χ^2/ NDF
Planar	10 000	51.99	203	89.1	2.93	2.86	236	249/139
Large diode	4 896	54.54	193	87.6	2.88	3.12	516	1300/139
Small diode	2 003	58.21	181	85.7	2.82	3.50	913	9600/139

Table 1: Parameters extracted from the C–V data with the GR grounded. For explanations see text.

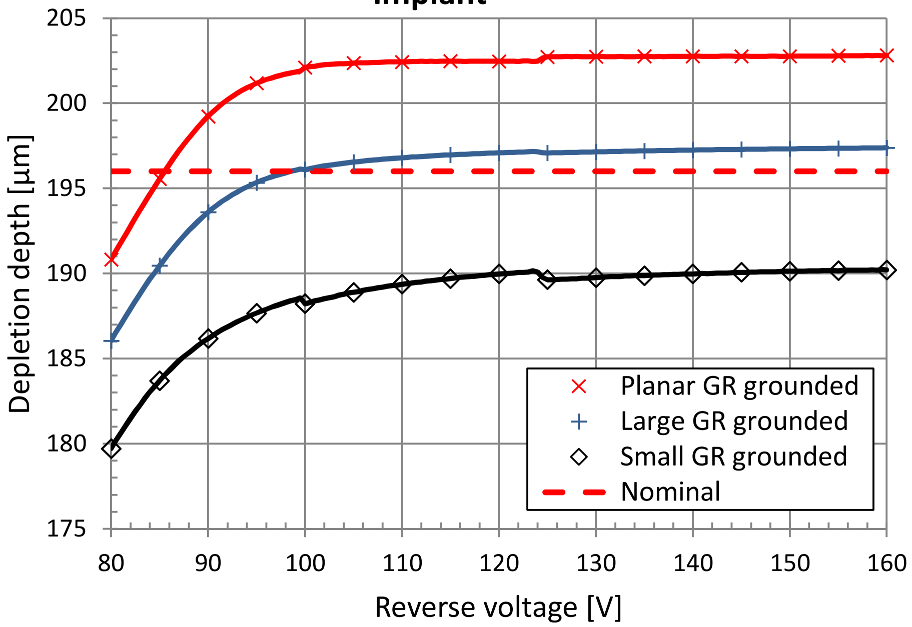
	N_0 [10^{12}/cm^3]	α [10^{12}/cm^4]	V_0 [mV]	$< N_D >$ [10^{12}/cm^3]	ΔN_D [10^{11}/cm^3]	χ^2/ NDF
Planar	2.92	−4.8	342	2.87	−0.48	94/138
Large diode	2.95	15.9	197	3.10	1.59	45/138
Small diode	2.95	53.6	−29	3.49	5.36	51/138

Table 2: Parameters extracted from the C–V data with the GR grounded for the fit using Eq. 6.

Nominal thickness

Depletion depth $w(V) = \frac{\varepsilon_{Si}}{C(V)}$ → $V > V_{dep}$ → **nominal thickness**

assumed a = $a_{implant}$ + distance between GR and implant window



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Small: Δ (expected – extracted active thickness) = +6 ± 3 µm → compatible