Determination of the p^+-spray doping profile using MOSFETs

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Motivation

- In n^+p and n^+n sensors positive oxide charges (N_{ox}) result in an electron accumulation layer → readout electrodes not isolated
- Surface radiation damage increases N_{ox} → p^+ implants to isolate n^+ implants

→ Knowledge of p^+-doping profile required to understand field close to interface + breakdown behaviour and pixel isolation after radiation damage

- Manufacturers (usually) do not communicate technology of p^+ implants (we typically only have the GDS files for the masks)

→ Back-engineering required to have this information

→ Reliable methods desirable to determine p^+-doping profiles

- For detailed simulation several additional parameters are required: N_{ox}, interface trap densities (D_{it}), mobility μ at Si-SiO_2 interface, surface resistivity of oxide

A reliable non-destructive method for p^+ doping determination is wanted

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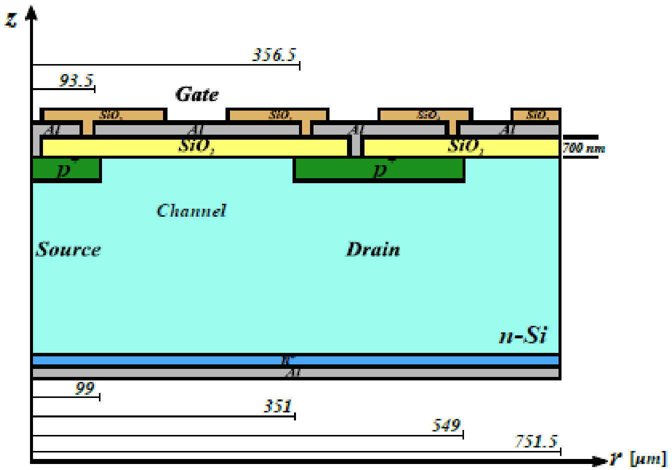
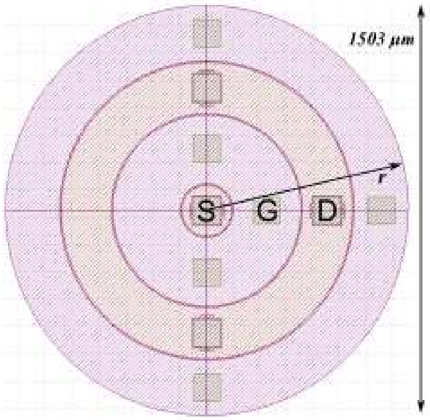
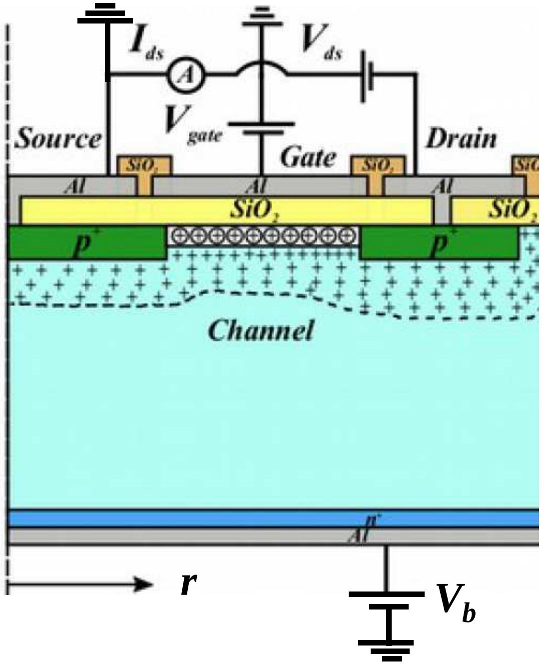
methods to determine the additional parameters for simulations

MOSFETs and measurement set-up







Circular MOSFET produced by HPK on <100> Si

- **no p$^+$ implant: M200P_04_HPKTS_1_MOSFET**
- **p$^+$ implant: M200Y_06_HPKTS_2_MOSFET**

Measure I_{ds} (V_{gate}) for different values of V_{back} (change of depletion depth)

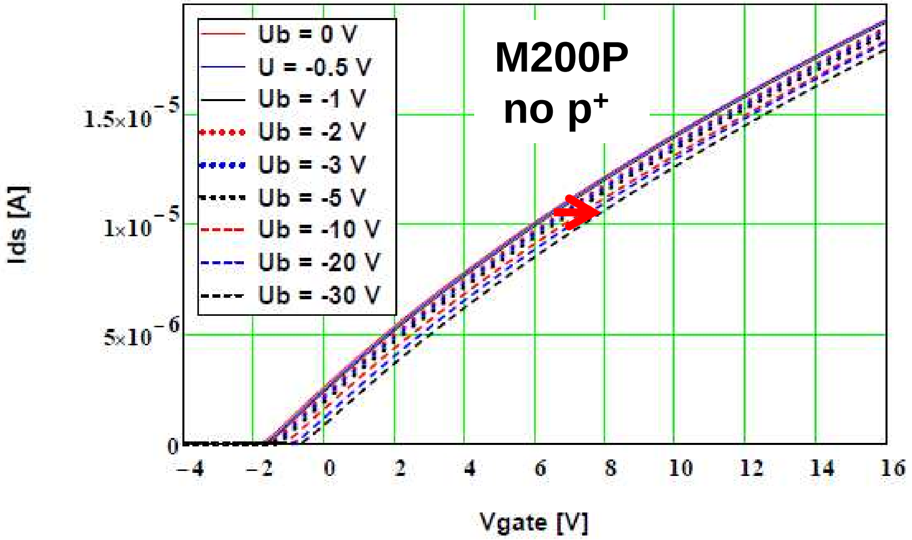
Comment: MOSFET has similar layout to segmented sensors, with additional feature that gate can be used to change Si-SiO$_2$ interface potential

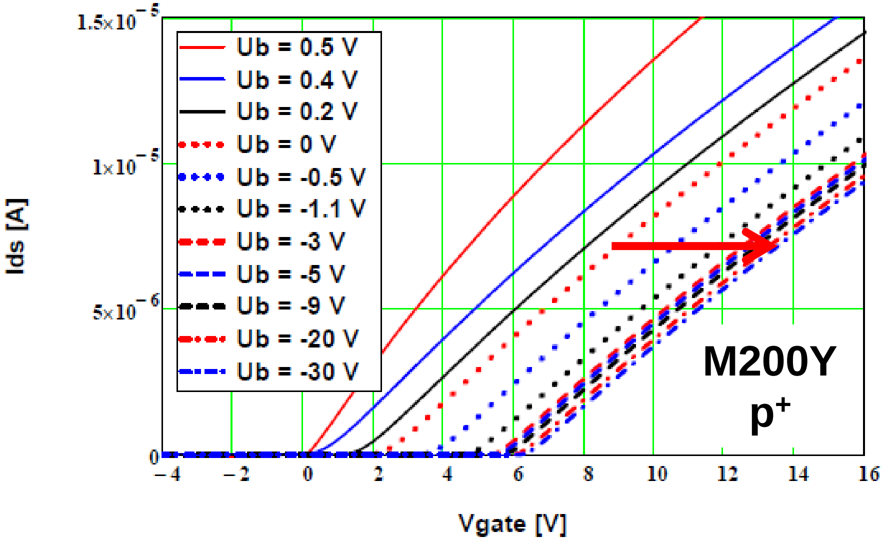
A simple measurement, which takes ~1/2 day

Examples for measured $I_{ds}(V_{gate})$ curves

Measurements for V_{gate}= 0 … 16 V

- V_b = 0 … -30 V for no p-spray
- V_b = 0.5 … -30 V for p-spray (wider range + finer V_b bins)





V_{gate}= 0 V → V_{gate}= 16 V

Comparison with/without p⁺ implant:

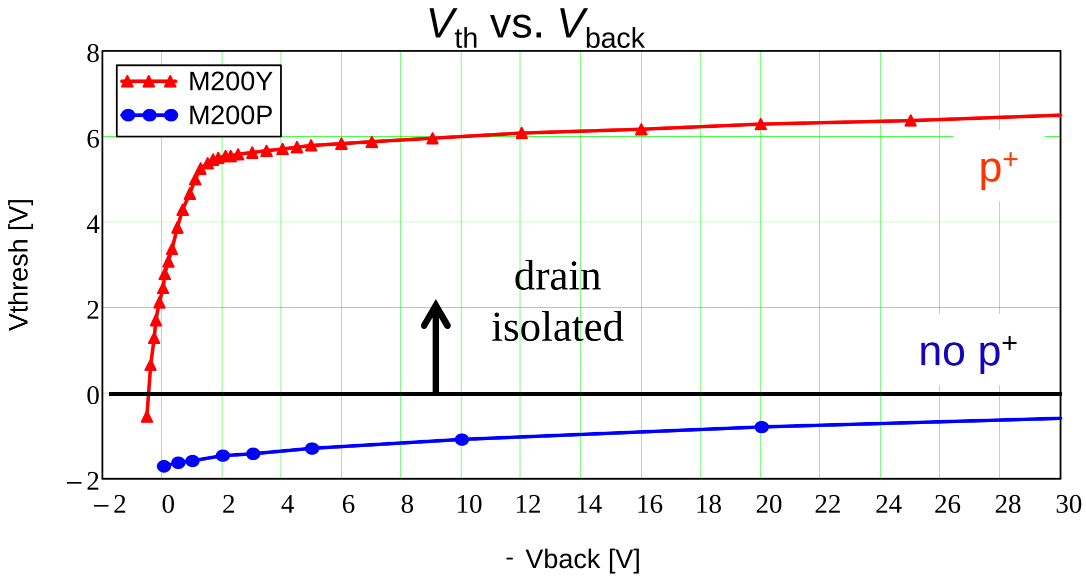
- **I_{ds} similar shape (except V_{back} = +0.5 V), but shift in V_{gate}**
- **Change of I_{ds} with V_{gate} much bigger for MOSFET with p⁺ implant!**

$I_{ds}(V_{gate})$ fits versus V_{back}

Using the Brews Charge-sheet model: $I_{ds} = \frac{W}{L} \cdot \mu \cdot C_{ox} \cdot \{V_{gate} - V_T(V_{back})\} \cdot V_{ds}$

Electron mobility at interface: $\mu(V_{gate} - V_T) = \mu_0/(1 + \frac{V_{gate} - V_T}{V_{1/2}})$

Circ. MOSFET width/length: $\frac{W}{L} = 2\pi/\ln(r_2/r_1) = 4.964$ **and** $C_{ox} = \varepsilon_{ox}/t_{ox} = 4.933$ **nF/cm²**



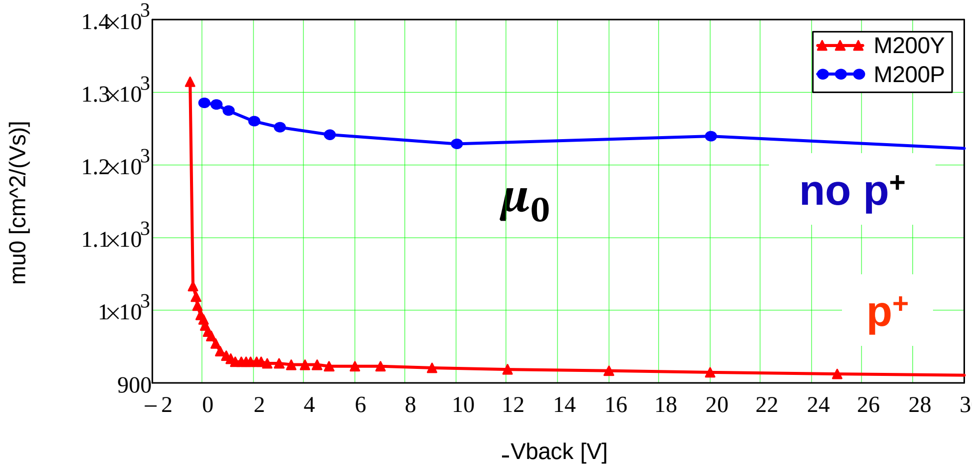
For $V_{gate} > V_T$ model describes data within ~0.1 % for p$^+$ and 0.5% for no p$^+$

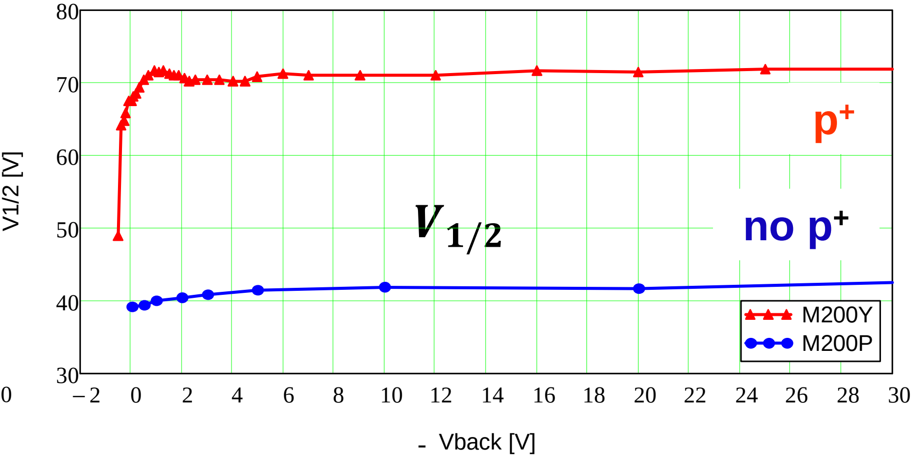
- no p$^+$: $V_T < 0$ for $V_b < 30$ V → "source - drain shorted"

- p$^+$: $V_T > 0$ for $V_b \geq 0$ V → "source - drain isolated"

Fit results for mobility

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





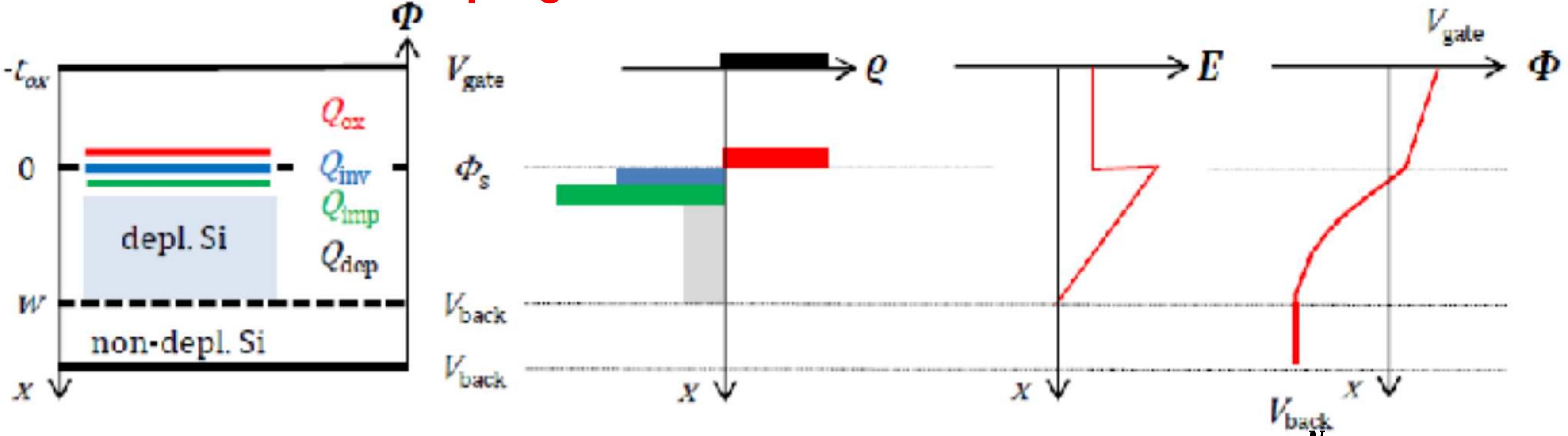
Differences in mobility behaviour:

- **no p$^+$: dominated by surface effects**
- **p$^+$: in addition, μ reduction due to high doping-density**

Comment: μ_e at interface very different to standard values in Synopsys TCAD !

Determination of p-spray dose [cm^{-2}] and N_{ox} [cm^{-2}]

Method 1: Uniform doping method



Potential at interface: $\Phi_s \approx 2\Phi_b + f_{ds}V_{ds}$, with $f_{ds} = 0.691$ and $\Phi_b = kT\cdot\ln(\frac{N_{dop}}{n_i})$

For uniform bulk doping N_0

Depletion depth: $w = \sqrt{\frac{2\,\varepsilon_{Si}}{q_0N_0}(\Phi_s - V_{back})}$ **(same formula as for planar diode)**

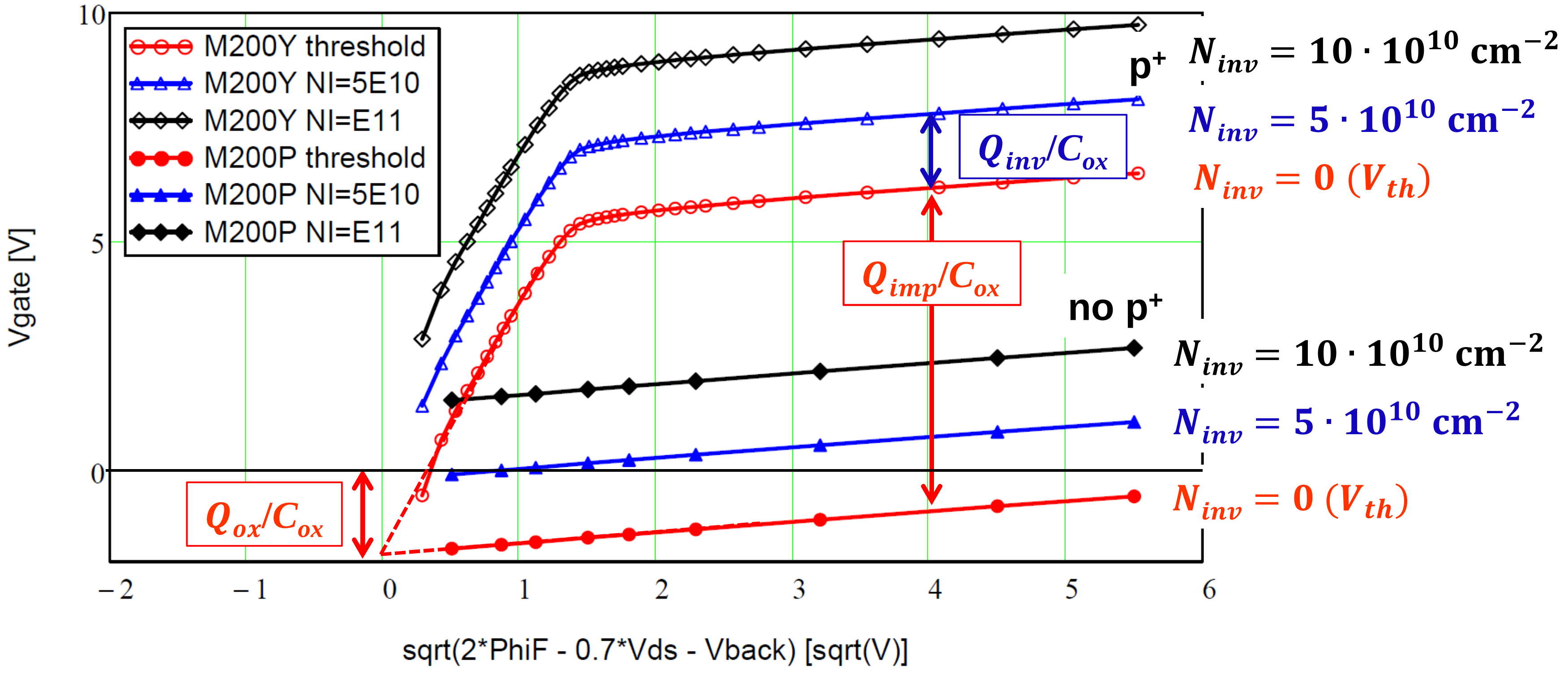
$$\boxed{V_{gate} = \Phi_s + \underbrace{E_{ox}t_{ox}}_{\substack{\text{Voltage drop}\\ \text{over oxide}}} = \Phi_s + \Big(\underbrace{\sqrt{2q_0\varepsilon_{Si}N_0\cdot(\Phi_s - V_{back})}}_{\substack{\text{charge depletion region}\\ \text{(bulk)}}} + \underbrace{Q_{imp}}_{\substack{\text{Charge}\\ \text{implant}}} + \underbrace{Q_{inv}}_{\substack{\text{Charge}\\ \text{inversion}}} - \underbrace{Q_{ox}}_{\substack{\text{Oxid}\\ \text{charge}}}\Big)/C_{ox};\quad C_{ox} = \varepsilon_{ox}/t_{ox}}$$

For given Q_{inv} (from I_{ds} and μ_e)

V_{gate} vs. $\sqrt{(\Phi_s - V_{back})}$ linear dependence

→ slope gives N_0 and intercept $N_{imp} + N_{inv} - N_{ox}$

Determination of p-spray dose [cm^{-2}] and N_{ox} [cm^{-2}]



Results: $N_0(\mathrm{M200P}) = 3.8 \cdot 10^{12}\ \mathrm{cm}^{-3}$; $N_0(\mathrm{M200}Y) = 3.6 \cdot 10^{12}\ \mathrm{cm}^{-3}$

$N_{imp} = 2.18 \cdot 10^{11}\ \mathrm{cm}^{-2}$; $N_1(\mathrm{M200}Y) = 1.9 \cdot 10^{15}\ \mathrm{cm}^{-3}$ → $d_{imp} = 1.15\ \mu m$

$N_{ox}(\mathrm{M200P}) = 6.5 \cdot 10^{10}\ \mathrm{cm}^{-2}$; $N_{ox}(\mathrm{M200}Y) = 6.5 \cdot 10^{10}\ \mathrm{cm}^{-2}$

Simple method → "only" p⁺ integral – value of Φ_S has to be assumed

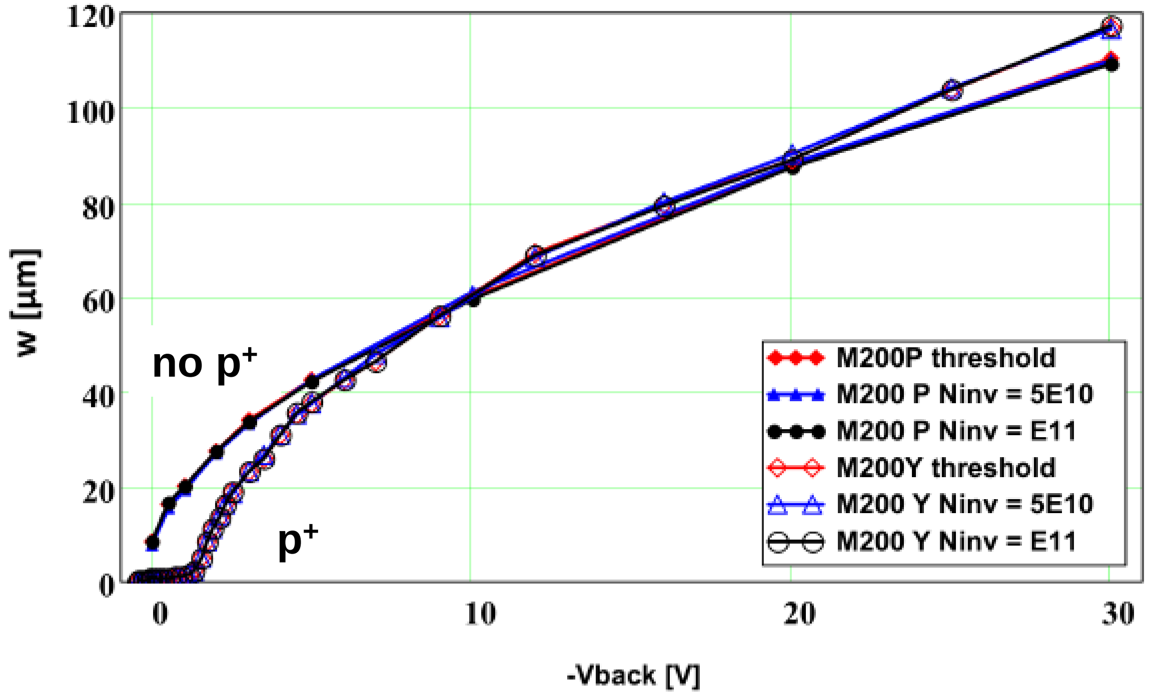
Depletion depth vs. V_{back}

Method 2: “differential”: M.Buehler et al., Appl. Phys. Let. 31(1977)848-850:

Assume: 1-dim. depletion approximation (and N_D ~ p → Debye correction later)

For N_{inv} fixed

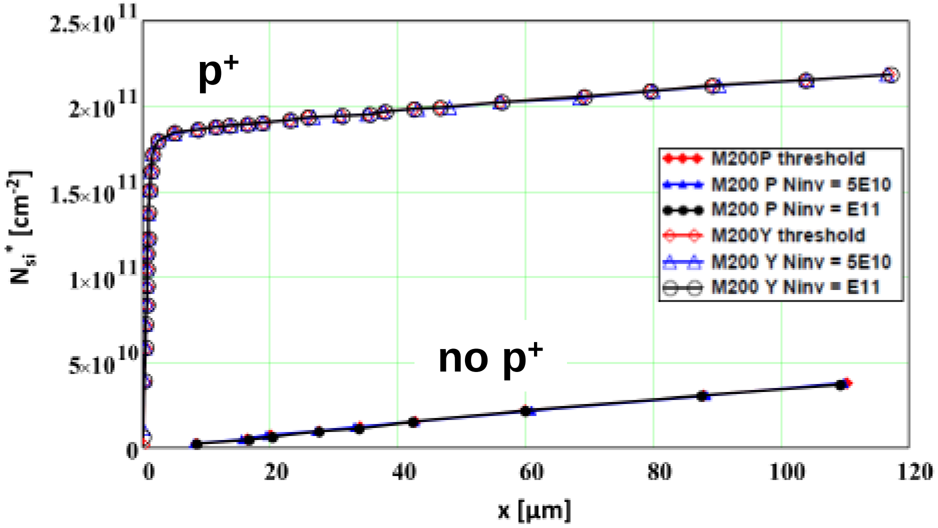
$$N_D(w) = \frac{C_{ox}{}^2}{q_0 \cdot \varepsilon_{Si}} \cdot \left(\mathrm{d}^2 V_{back}/\mathrm{d}V_{gate}{}^2\right)^{-1} \; ; \; x = w = \frac{\varepsilon_{Si}}{\varepsilon_{ox}} \cdot t_{ox} \cdot \frac{\mathrm{d}V_{back}}{\mathrm{d}V_{gate}}$$

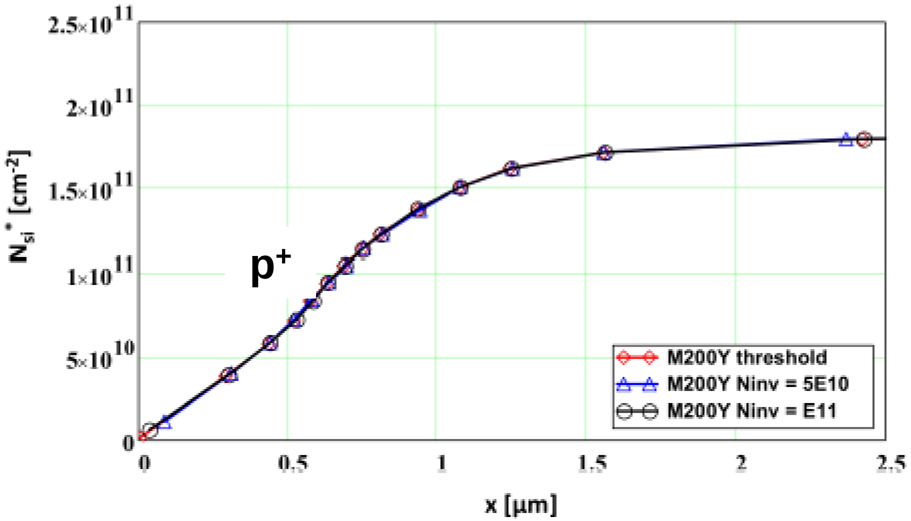


w (1st derivative) well determined - differences for w < 2 µm

Integral of doping profile

$$\mathbf{x} = \frac{\varepsilon_{Si}}{\varepsilon_{ox}} \cdot t_{ox} \cdot \frac{\mathrm{d}V_{back}}{\mathrm{d}V_{gate}} \ \ \textbf{and} \ \ N^* = \int_0^x N_D(\xi)\,\mathrm{d}\xi = \frac{C_{ox}}{q_0}\left(V_{gate}(x) - V_{gate}(0)\right)$$





Method uses only 1^{st}derivative and extrapolation to x → 0

Dopant integral, which is most relevant, is well determined;

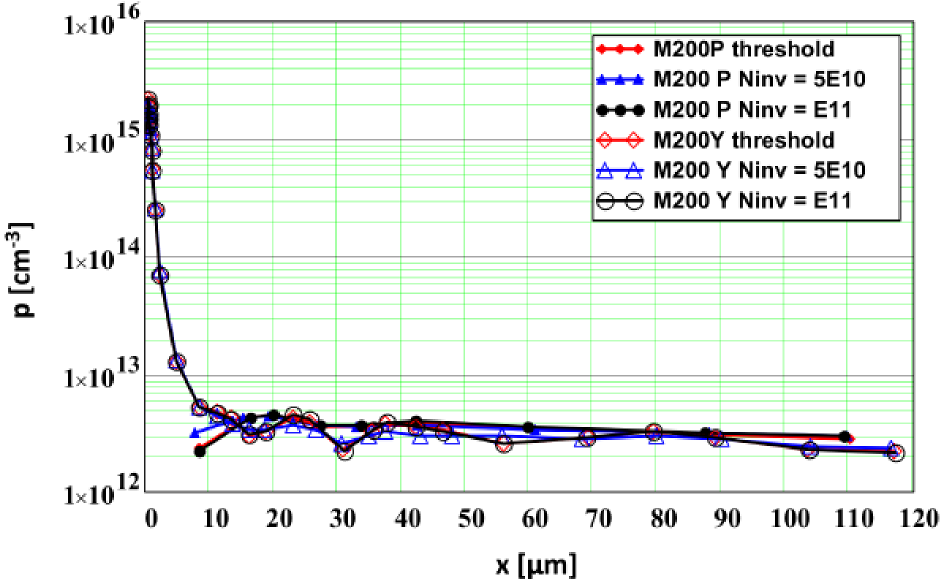
can be probed at distances < 1 µm from Si-SiO$_2$ interface

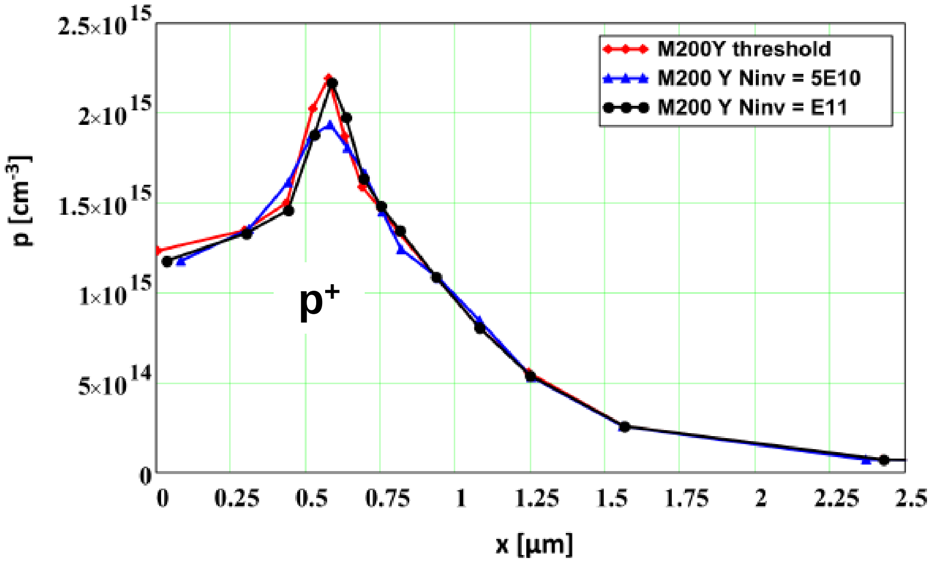
Density of free charge carriers (holes)

Like *C-V* for n^+p-diodes, also n-MOSFET measurements determine the hole density

(for rapid variation of $N_D(x)$ due to diffusion $N_D(x) \neq p(x)$ "Debye correction")

$$\boxed{p(x) = \frac{C_{ox}{}^2}{q_0 \cdot \varepsilon_{Si}} \cdot \left(\mathrm{d}^2 V_{back} / \mathrm{d}V_{gate}{}^2\right)^{-1} \quad \text{and} \quad x = \frac{\varepsilon_{Si}}{\varepsilon_{ox}} \cdot t_{ox} \cdot \frac{\mathrm{d}V_{back}}{\mathrm{d}V_{gate}}}$$





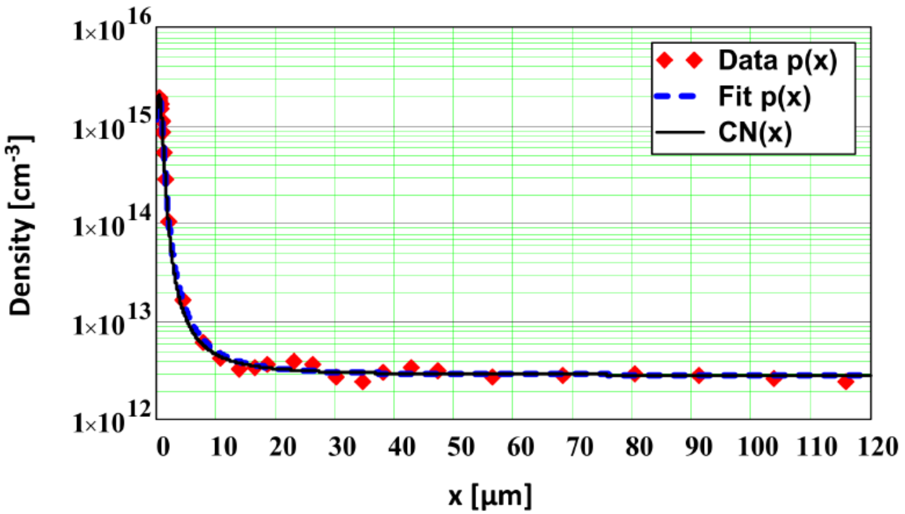
***p*(*x*) results (2nd derivative!) very sensitive to data quality;**

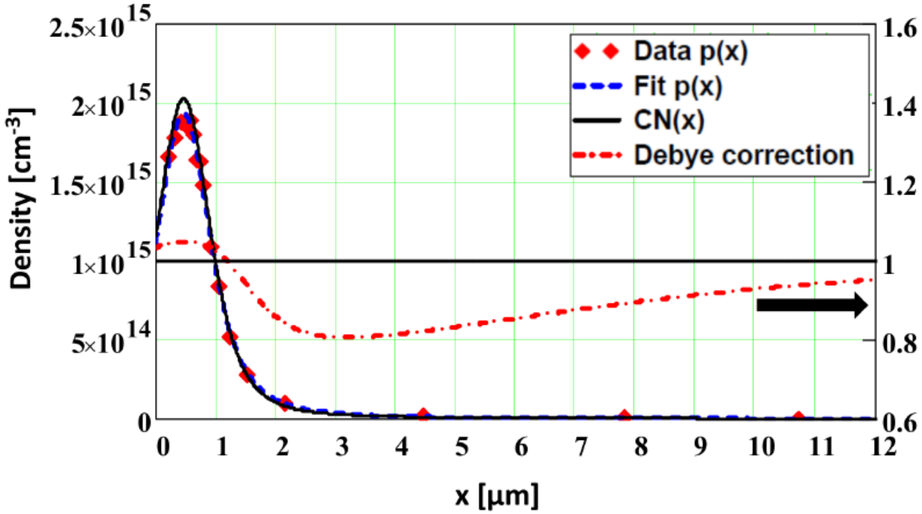
extraction of *p*(*x*) not too reliable (e.g. V_{back} has to be known to ~1 mV)

Dopant density

Relation between doping density and hole density (drift current = diffusion current)

$$N_D(x) = p(x) - \frac{\varepsilon_{Si}\, kT}{{q_0}^2} \frac{\mathrm{d}^2 \ln(p(x))}{\mathrm{d}x^2}$$





To obtain smooth results *p*(*x*) was parametrised by a phenomenological function

Debye correction < 20 %, similar to the *p*(*x*) determination uncertainty
→ correction not straight forward and not too relevant

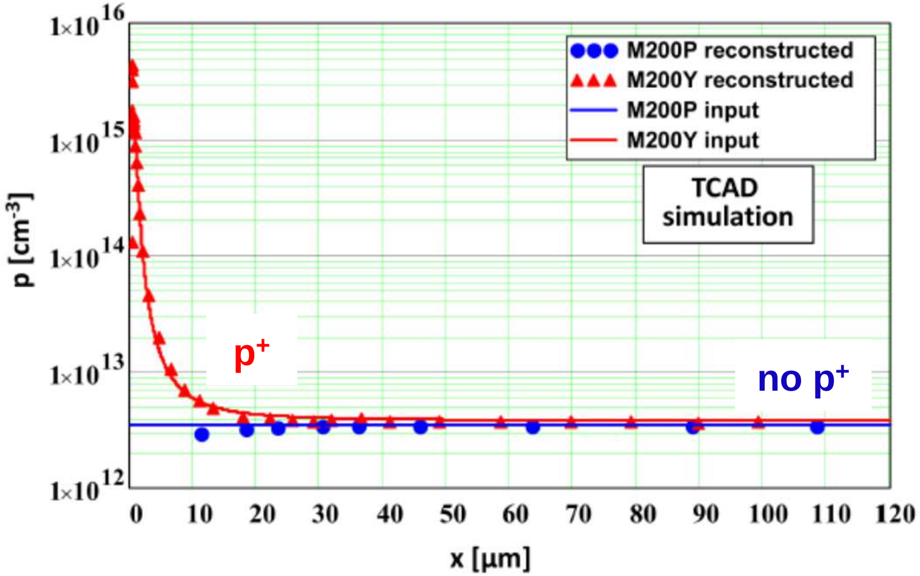
TCAD simulations

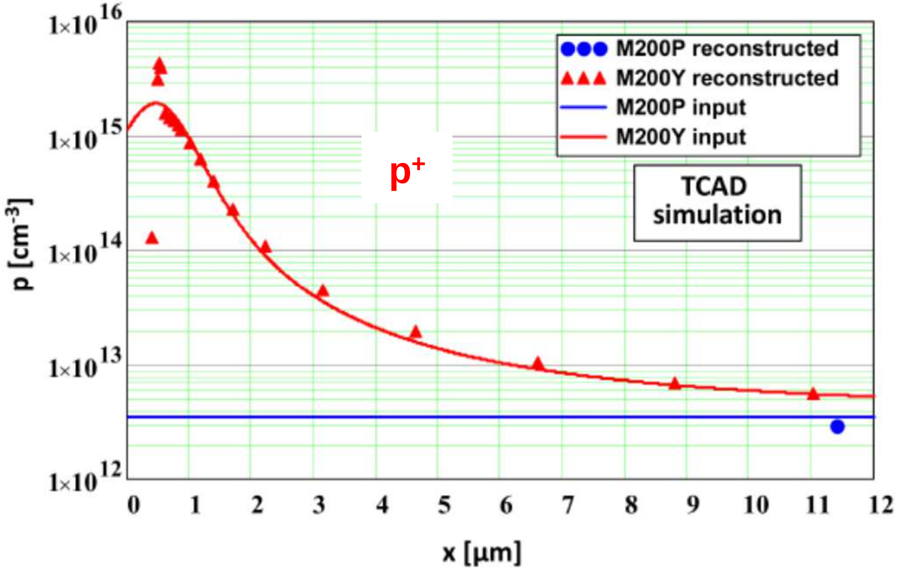
Analysis methods have been verified by TCAD simulations

Standard Synopsys parameters for $\mu_e(E)$ quite different to results

→ $I_{ds}(V_{gate}, V_{back})$ curves only qualitatively reproduced!

→ As check compare TCAD input values to results of analysis of TCAD data





Satisfactory, but not perfect agreement

→ To achieve simulations in agreement with data is a major challenge
(and requires significant computing resources)

Conclusions and possible next steps

Results relevant for understanding the isolation of n^+ implants in n^+p and n^+n Si sensors:

- **Integrated p^+ doping and doping profile to distances < 1 µm from Si-SiO_2 interface determined using a circular MOSFET**
- **Dependence of electron mobility in inversion layer as a function of the electric field normal to the Si-SiO_2 interface determined**
- **Oxide charge density N_{ox} determined**
- **Analysis methods verified using TCAD simulations**

Possible extension of the work:

- **Compare results to other methods, e.g. Spreading Resistance Measurement**
- **Irradiate MOSFETs with X-rays under bias to study the influence of surface damage on n^+ implant isolation under "detector operating conditions"**
- **Investigate if method can be used to study effective doping profiles in hadron-irradiated MOSFETs and compare to results from TCT, shallow beam, C-V-f and TCAD simulations (study of B-removal ???)**

! Comments and suggestions welcome !

Paper: E. Fretwurst et al., Determination of the p spray profile for n^+p silicon sensors using a MOSFET, arXiv 1704.01829 and submitted to NIM-A