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PHYSICS AT THE TERA SCALE
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Investigation of the insulator layers for segmented silicon sensors before and after X-ray irradiation

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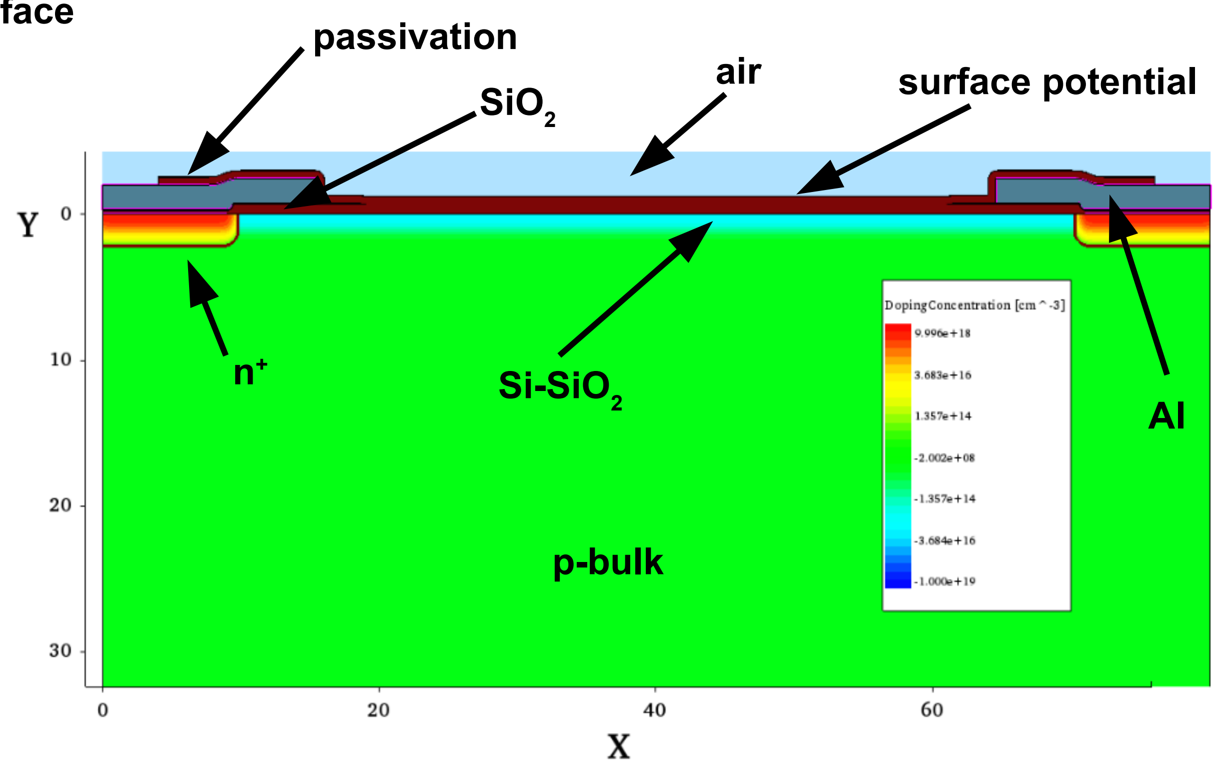
Motivation

- **Instabilities of segmented silicon sensors have been observed which can be depend on environment and time e.g:**
  - **- Dependence of the breakdown voltage on humidity and ramping speed**
  - **- Dependence of leakage current on humidity**
  - **- Dependence of charge sharing and charge loss on humidity**

- **Instabilities caused by changes of the potential distribution on the sensor surface and of the charge distribution at the Si-SiO_2 interface**

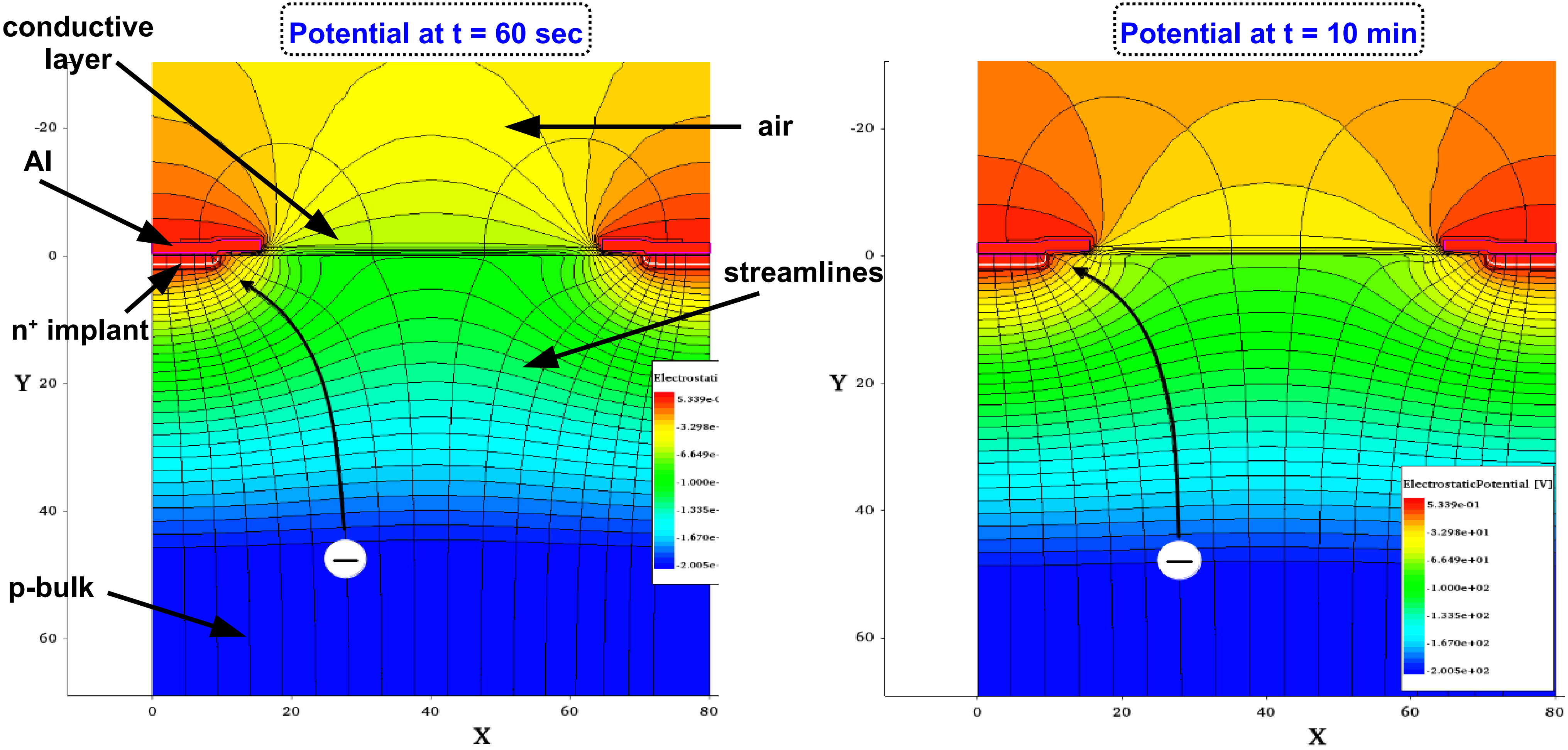
- **This work:**
  1. **Surface resistivity (surface potential)**
     - **- GCD (Gate Controlled Diode)**
     - **- MOSFET**
  2. **Charges at the Si-SiO_2 interface (N_{ox})**
     - **- Dependence on X-ray dose**
     - **- Dependence on E-field and time**



Effects of surface potential

- Simulation example of time dependent surface potential
  - AC coupled n^+-p sensor with p-spray ($N_{p\text{-spray}} = 5\cdot10^{11}\ \mathrm{cm}^{-2}$), $N_{ox} = 1\cdot10^{10}\ \mathrm{cm}^{-2}$
  - Conductive layer of 10 nm on top of passivation with $R_\square \approx 7\cdot10^{14}\ \Omega$
  - Voltage ramp: - 10 V/s up to - 600 V and then constant at - 600 V

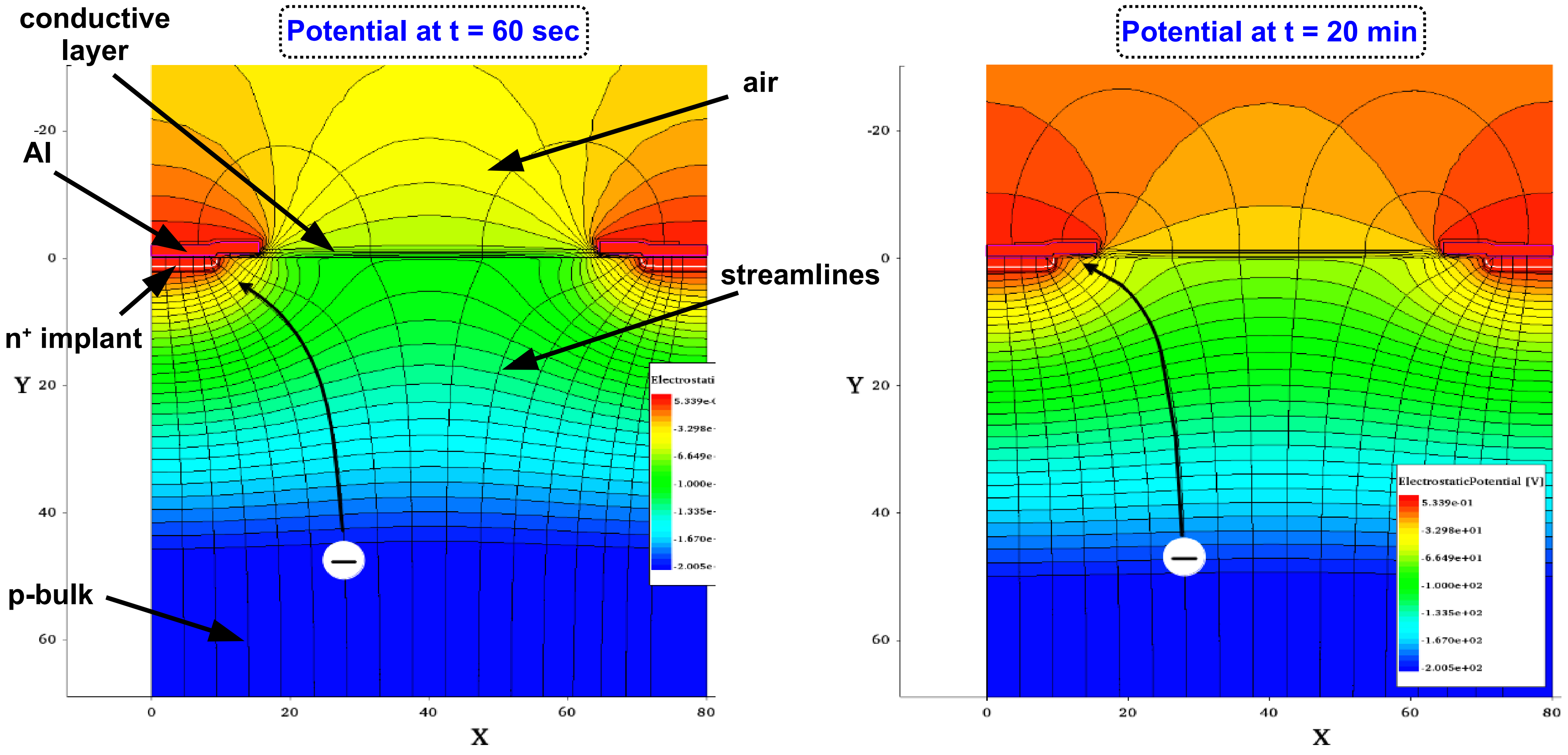
- pitch 80 µm
- width 18 µm
- thickness 200 µm
- $N_A = 3.4\cdot10^{12}\ \mathrm{cm}^{-3}$



Potential at t = 60 sec

Potential at t = 10 min

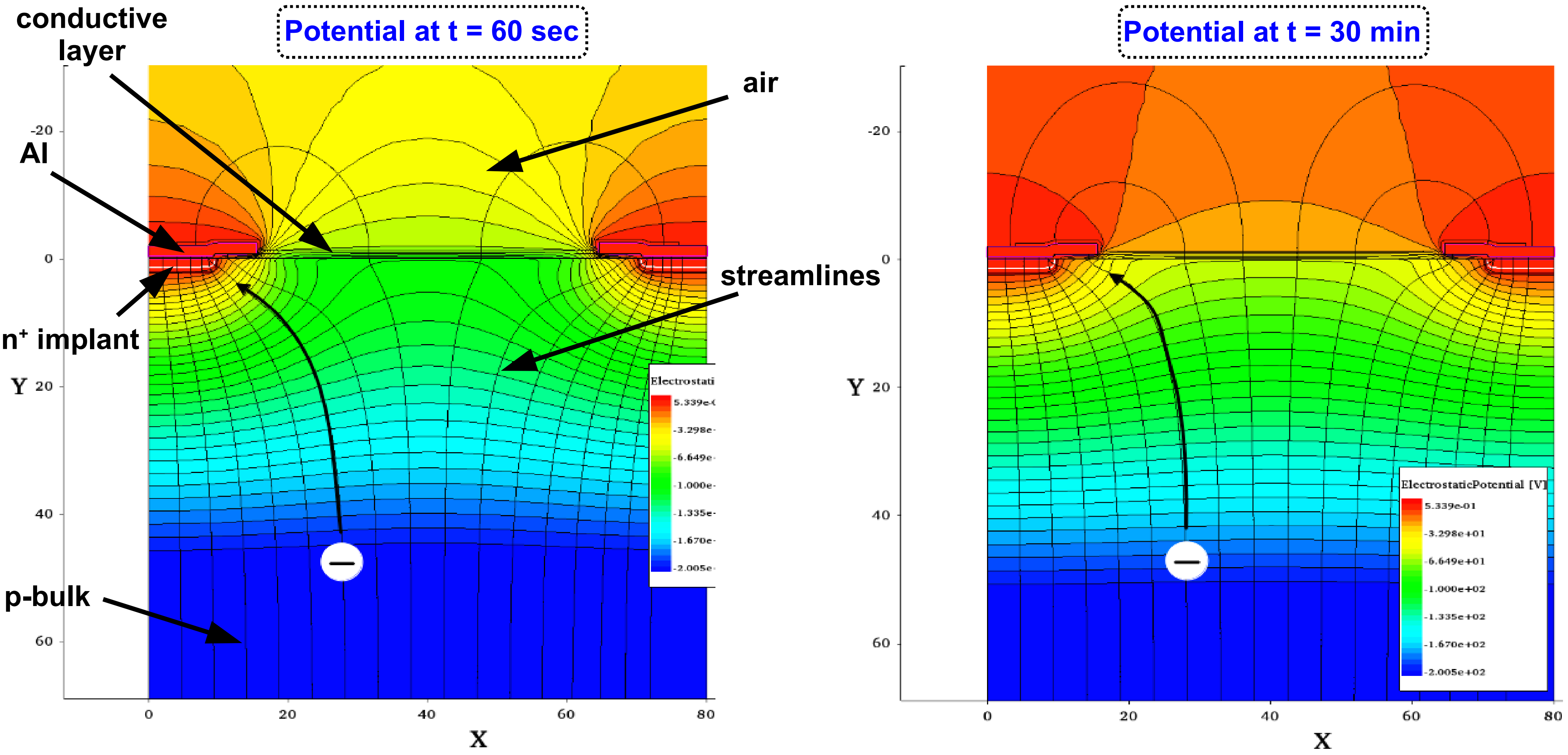
Effects of surface potential



Potential at t = 60 sec

Potential at t = 20 min

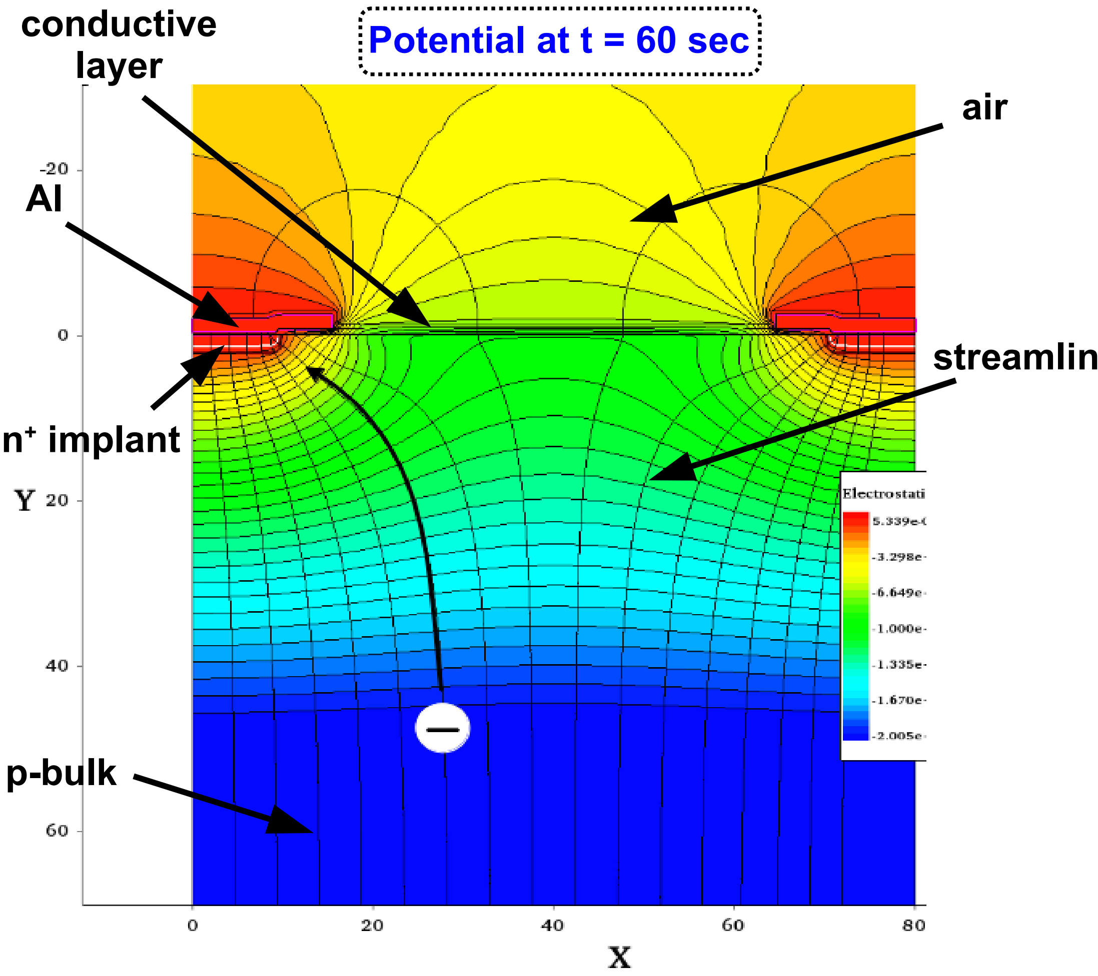
Effects of surface potential


Potential at t = 60 sec

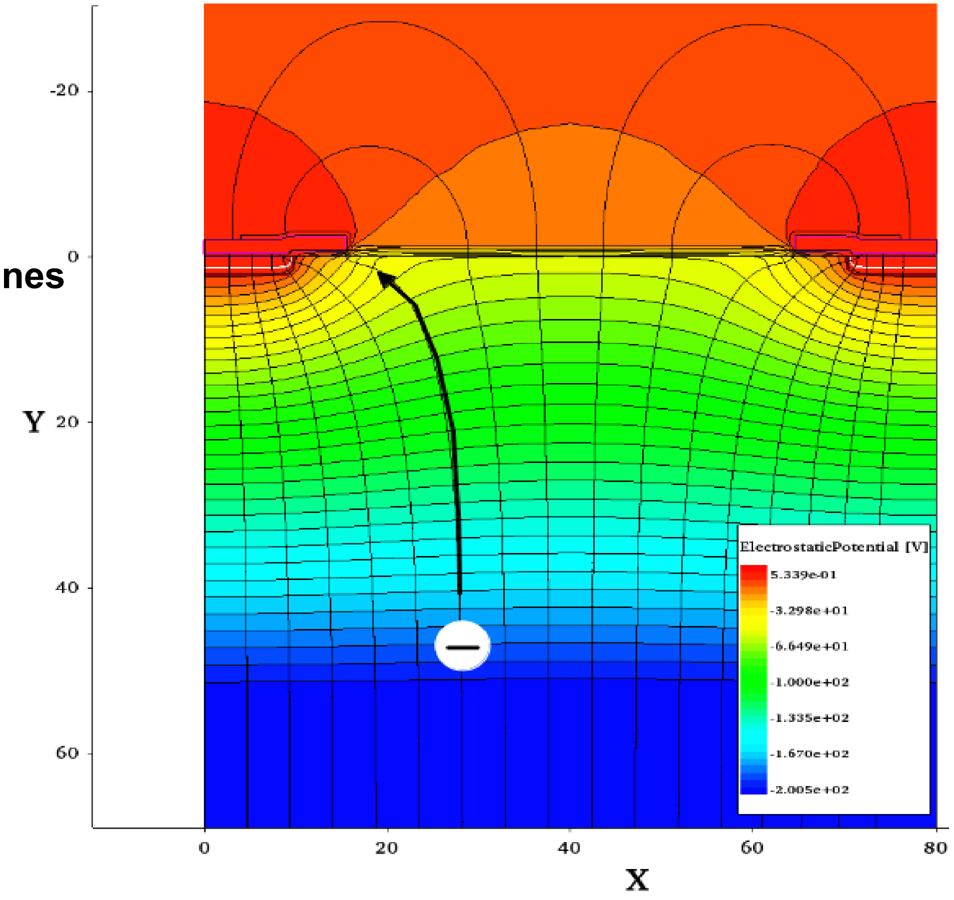
Potential at t = 30 min

Effects of surface potential

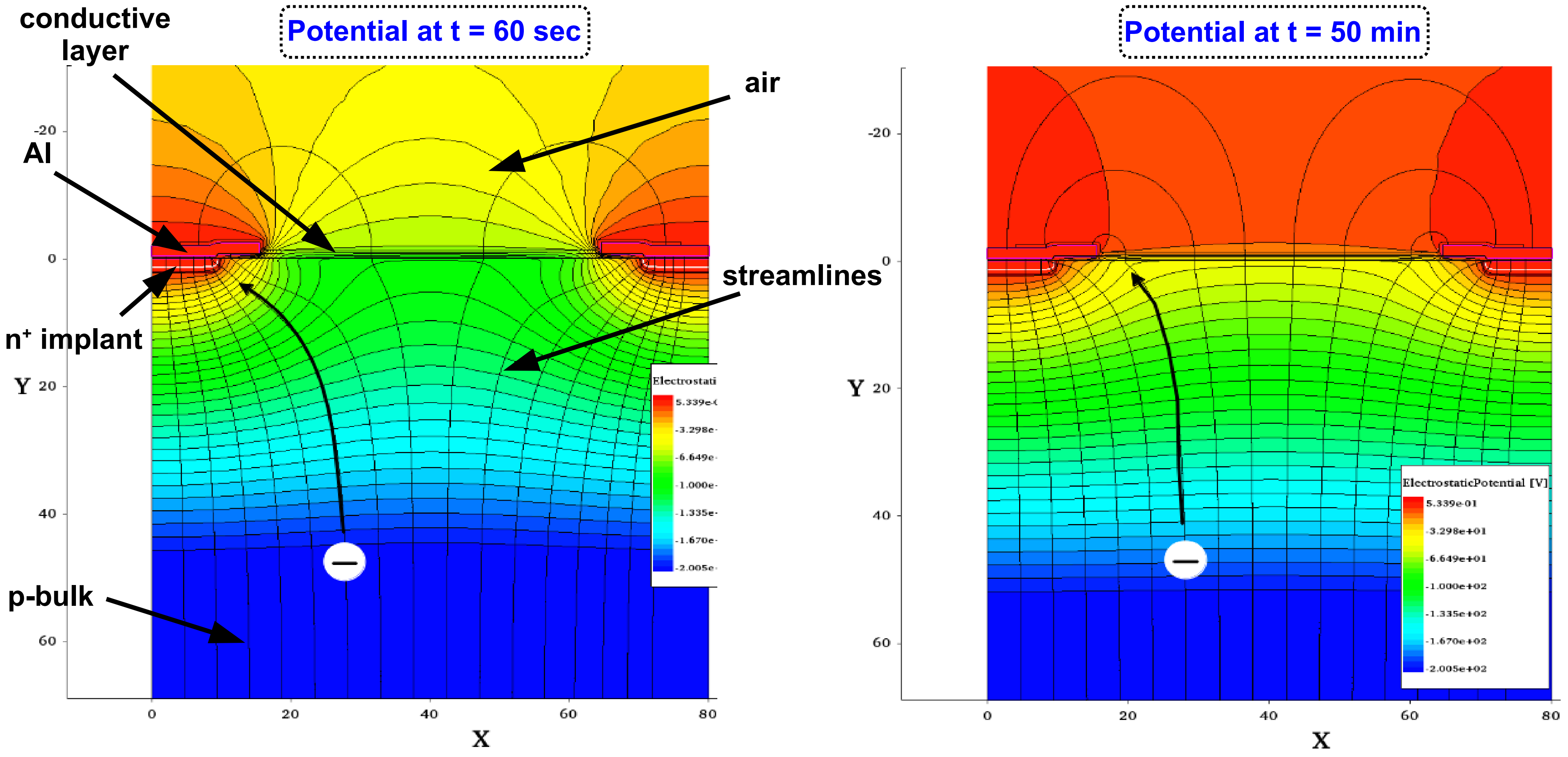
Potential at t = 60 sec



Potential at t = 40 min

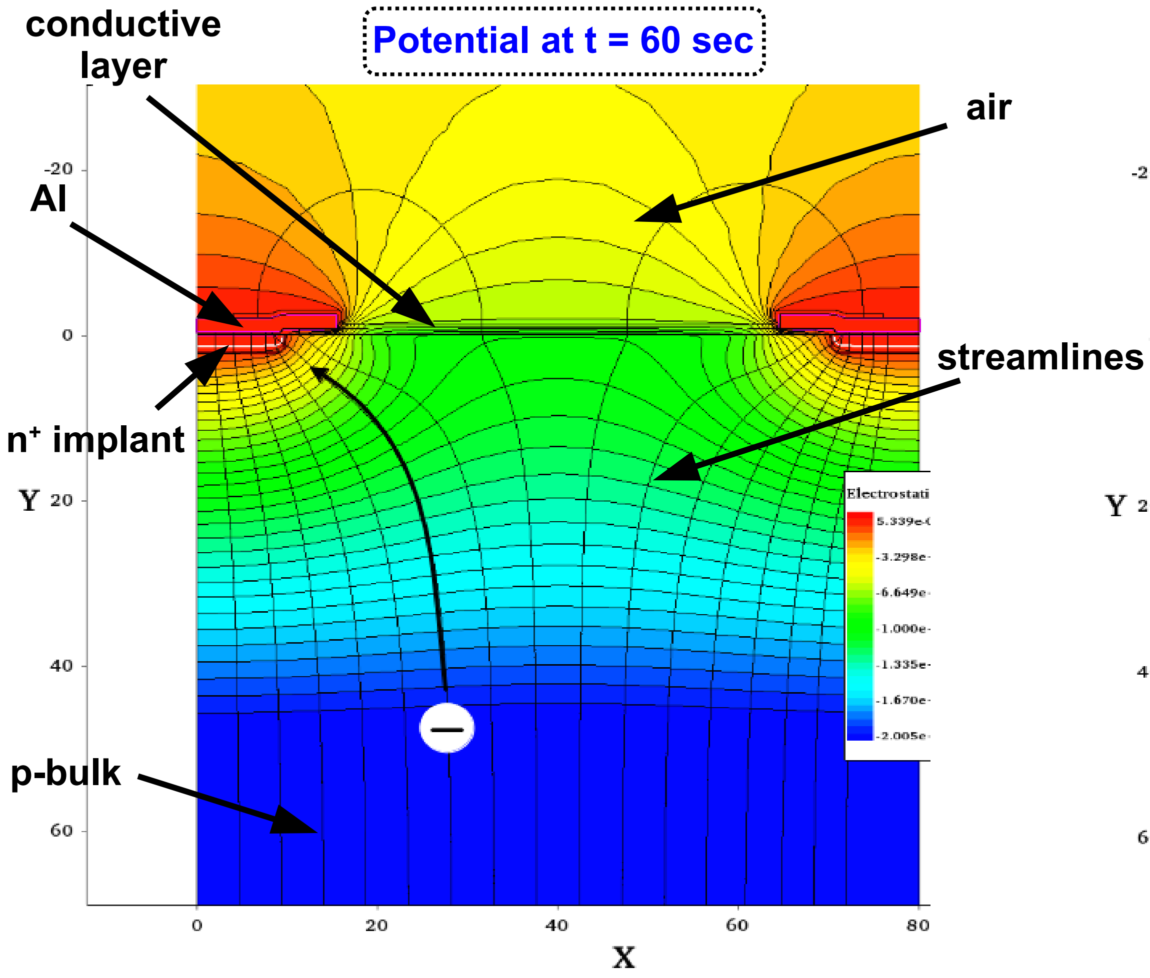


Effects of surface potential

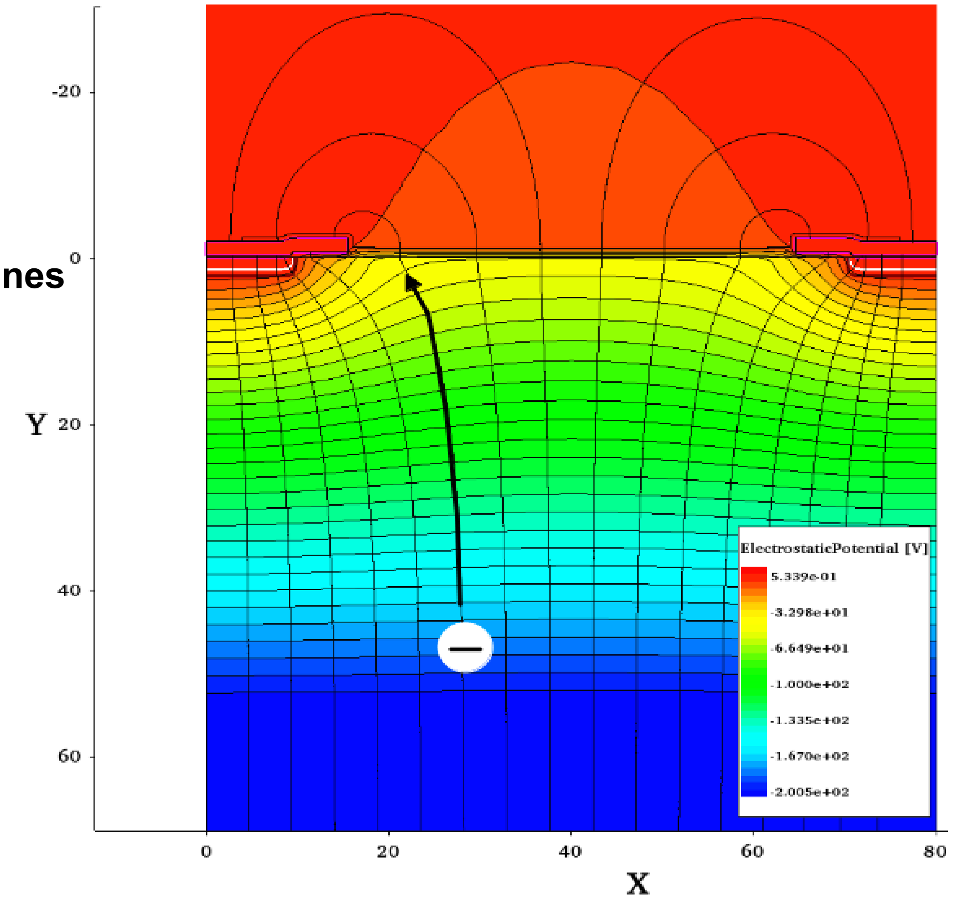


Effects of surface potential

Potential at t = 60 sec

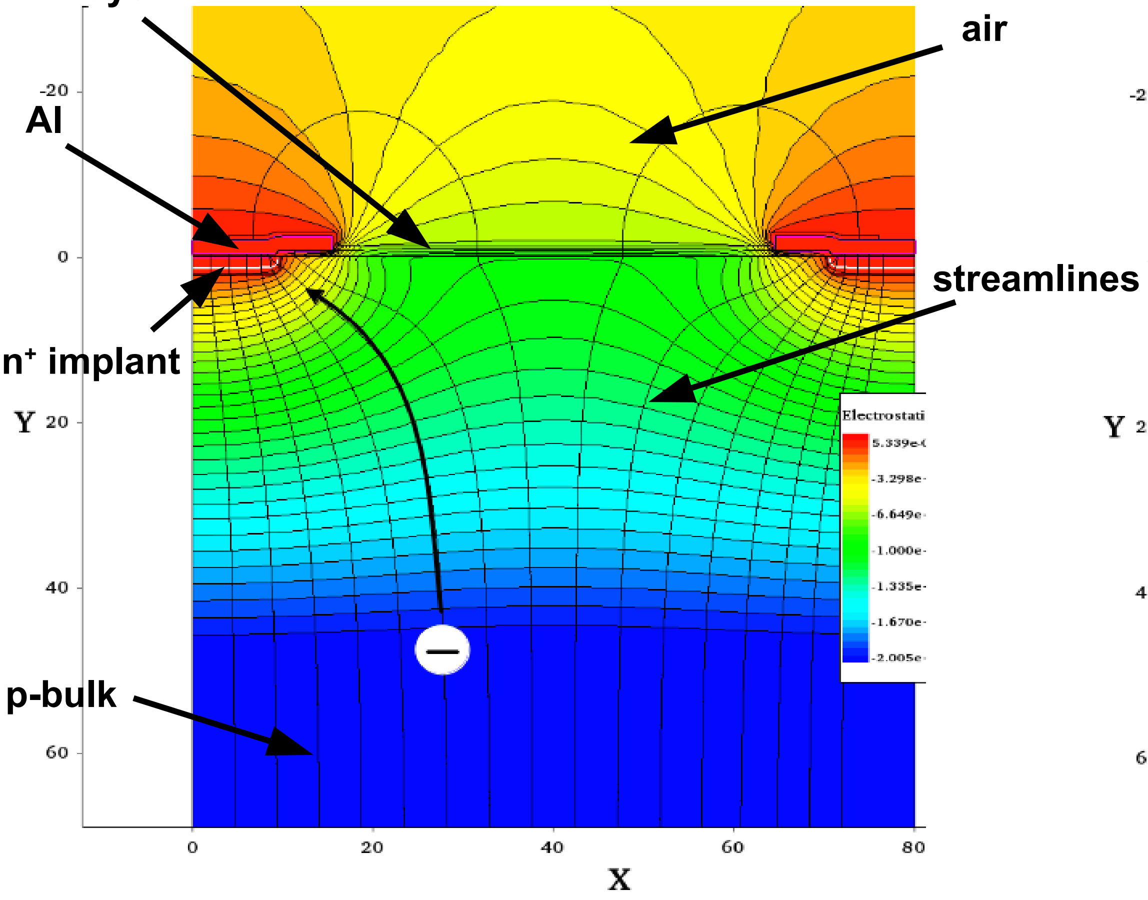


Potential at t = 60 min

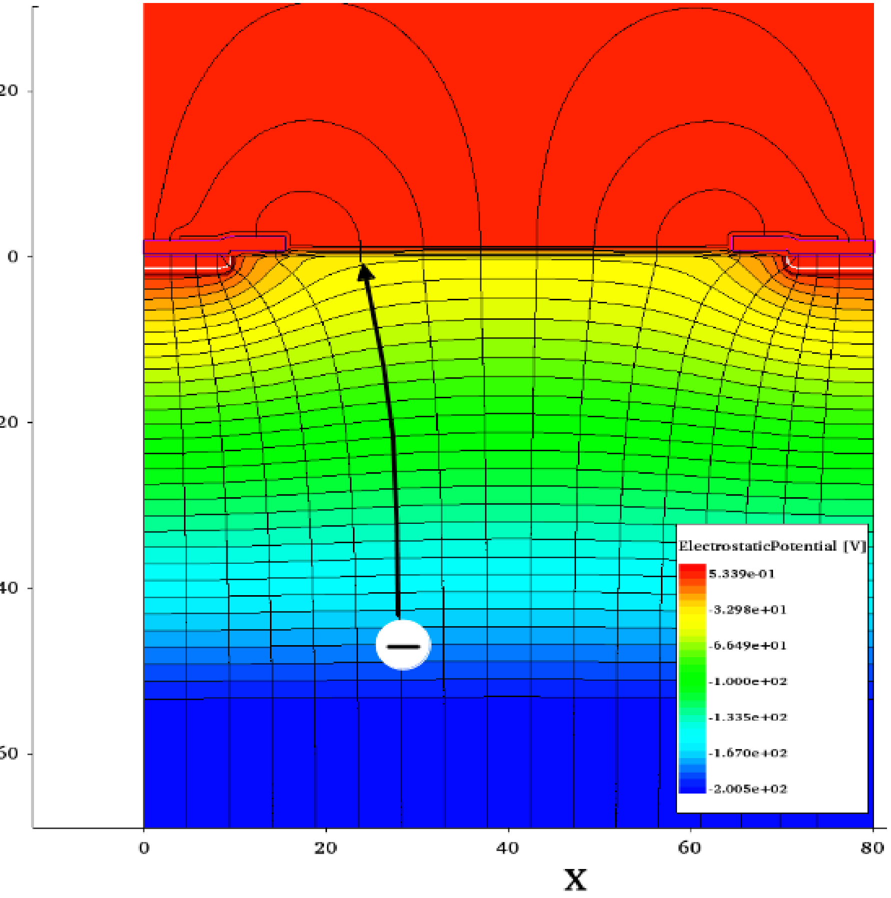


Effects of surface potential

Potential at t = 60 sec



Potential at t = 120 min



- **Most streamlines end at implant**

- **Many streamlines end at Si-SiO_2 interface**
  → charge sharing, charge losses

E-field in the silicon sensitive to surface conditions. For $R_\square \approx 7\cdot10^{14}\,\Omega$ it takes about 60 min to reach steady-state on surface.

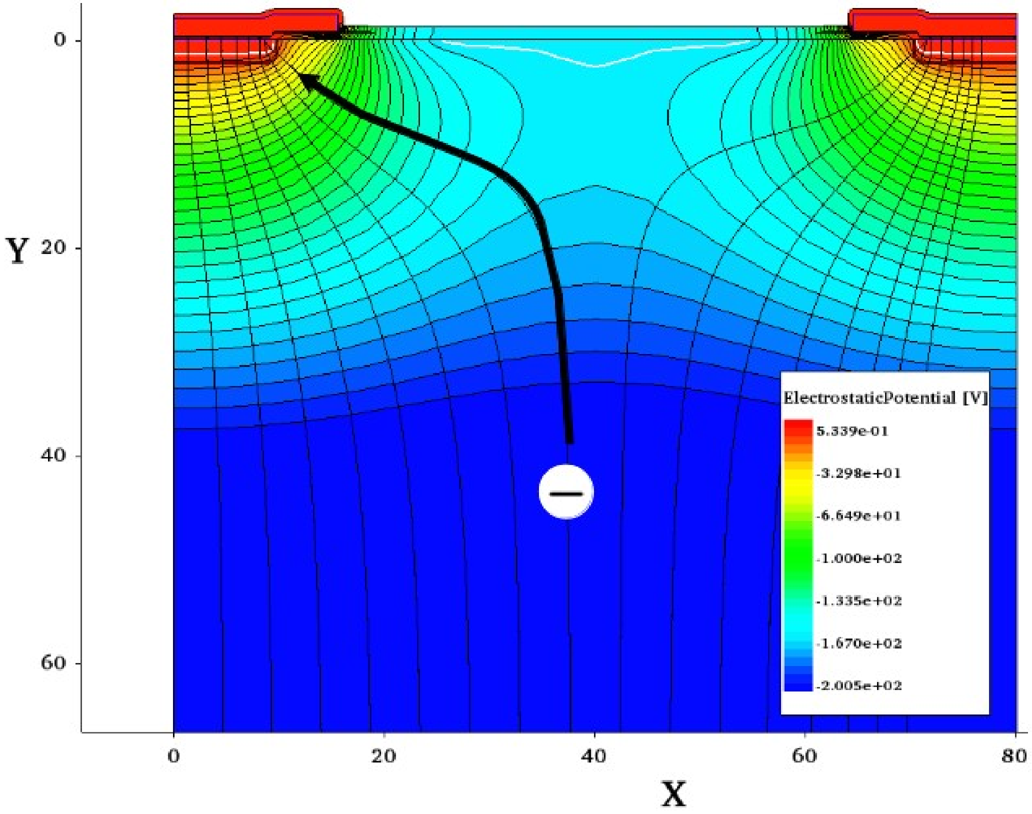
⚠

Effects of N_{ox}

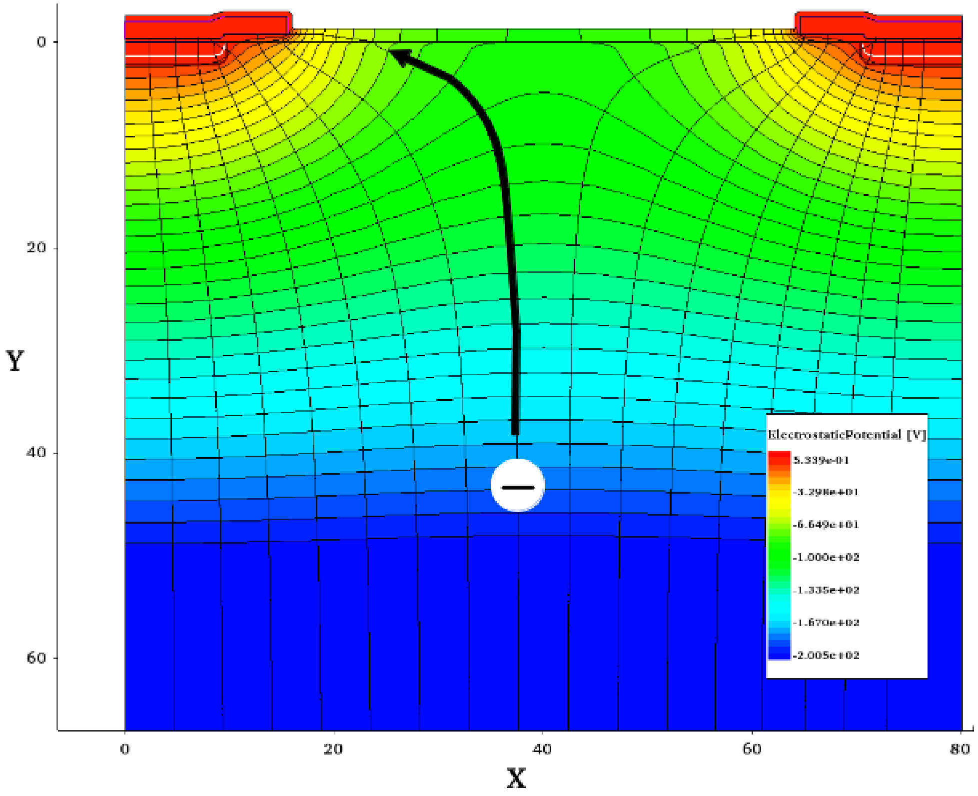
- Simulation example of oxide charge dependence
  - AC coupled n^+-p sensor with p-spray ($N_{p\text{-}spray} = 5\cdot10^{11}$ cm^{-2})
  - Neumann boundary conditions ($E_n = 0$)

- pitch 80 µm
- width 18 µm
- thickness 200 µm
- $N_A = 3.4\cdot10^{12}$ cm^{-3}

Potential at - 600 V, $N_{ox} = 1\cdot10^{10}$ cm^{-2}



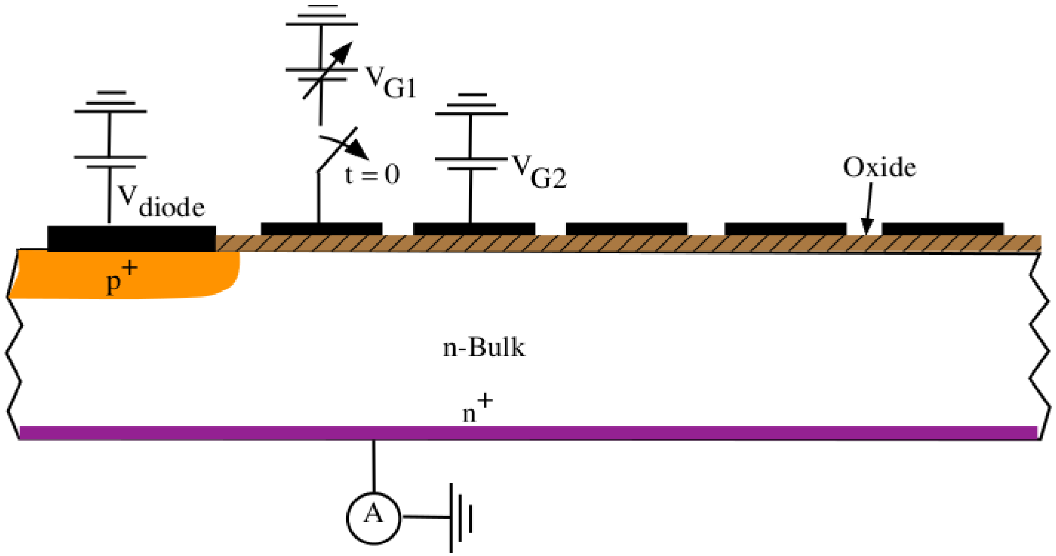
Potential at - 600 V, $N_{ox} = 5\cdot10^{11}$ cm^{-2}

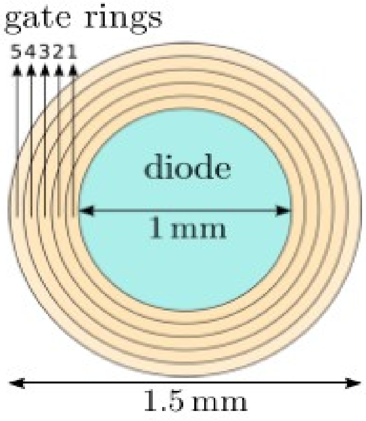


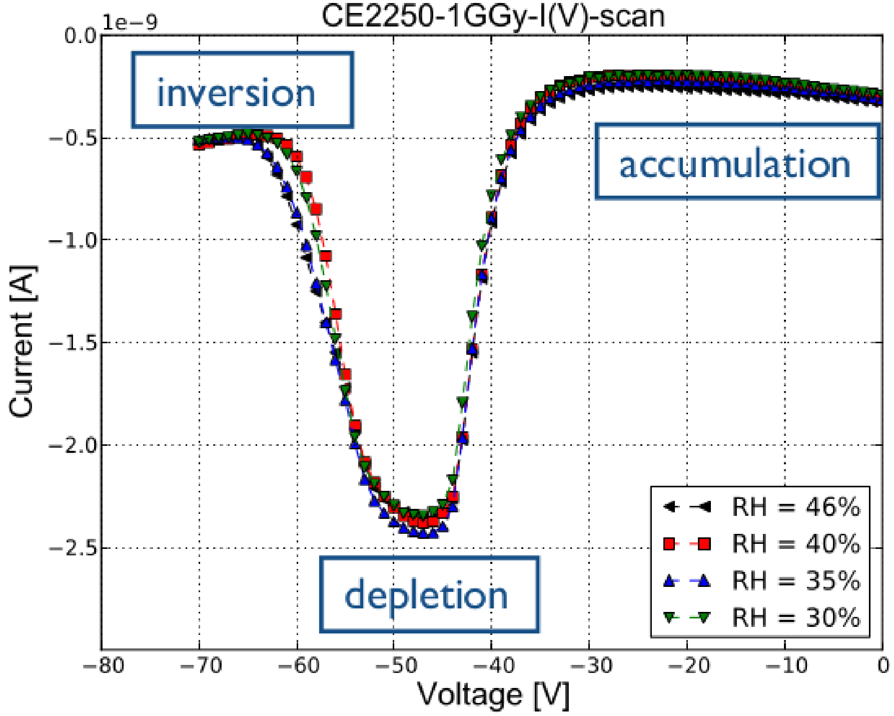
E-field in the silicon sensitive to oxide charges. Experimental observation of change of charge collection with N_{ox} → talk by A. Junkes at last RD50 meeting.

Surface resistivity: GCD

- **Circular GCD with 5 gate rings produced from CiS**
  - **- Diameter of diode: 1 mm**
  - **- Width of rings: 50 µm**
  - **- Distance between rings: 5 µm**
  - **- Insulator: 350 nm SiO_2 + 50 nm Si_3N_4**
  - **- n-type doping: ≈ $1\cdot10^{12}$ cm^{-3}**
  - **- Irradiated to 1 GGy**







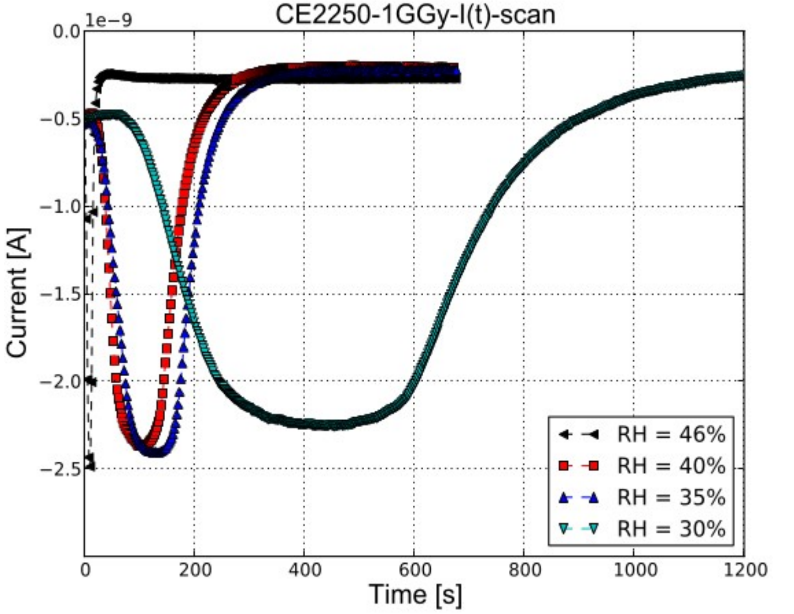
1. I_{GCD} as function of gate voltage V_{G1} on the first ring (V_{diode} = V_{G2} = - 12 V)

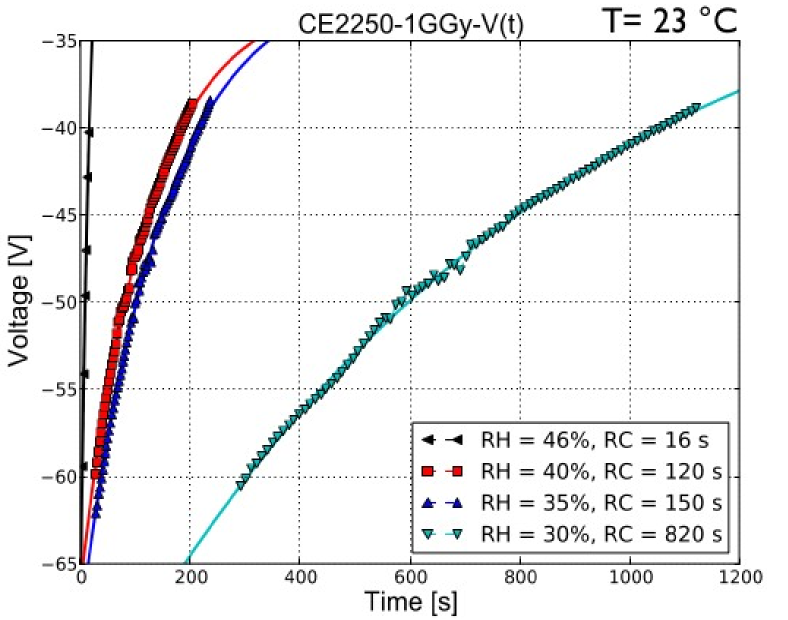
Surface resistivity: GCD

2. Bias V_{G1} into strong inversion (- 70 V) and measure I_{GCD} as function of time after disconnecting the gate probe from the voltage source
3. Determine V_{G1} (t) from steps 1 and 2
4. Determine the time constant $\tau = R_{surf} \cdot C_{G1}$ where C_{G1} is the capacitance of the gate to the bulk
5. Calculate the sheet resistance $R_\square$ for the 5 µm wide insulator

Relative humidity RH [%]	30	35	40	46
Discharge time [s]	820	150	120	16
R_{surf} [10^{12} Ω]	50	9.1	7.3	0.97
$R_\square$ [10^{15} Ω]	66	12	9.7	1.3

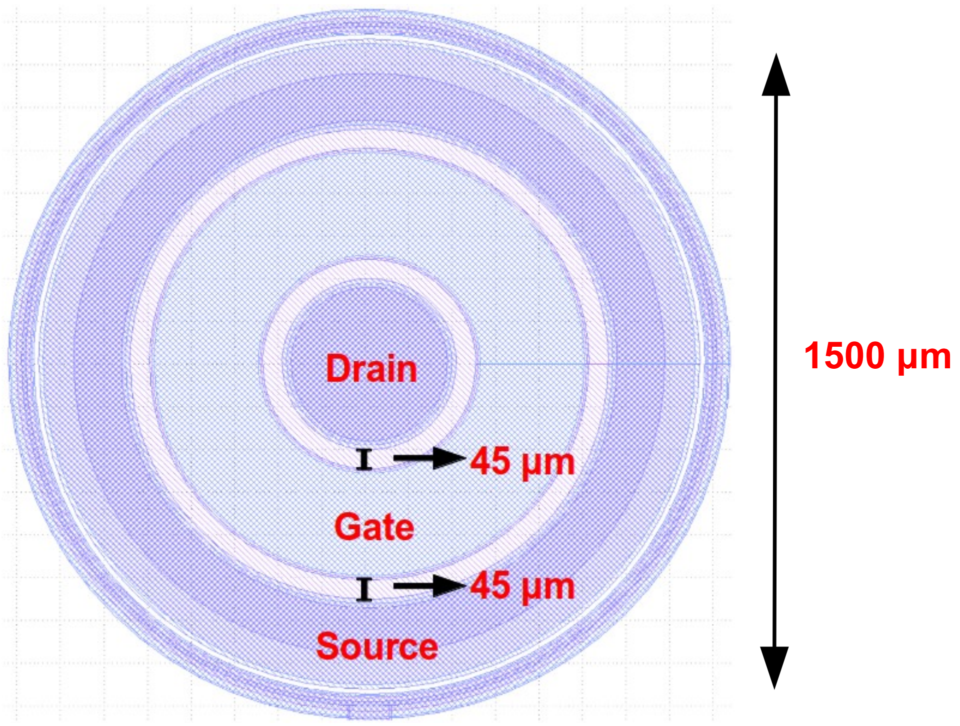
- The value of the sheet resistance $R_\square$ increases by a factor of ~ 50 when RH changes from 46 to 30 %
- The described measurements are possible only for irradiated GCDs (high surface current due to interface traps) and in limited V_{G1} range where the Si under the SiO_2 is depleted



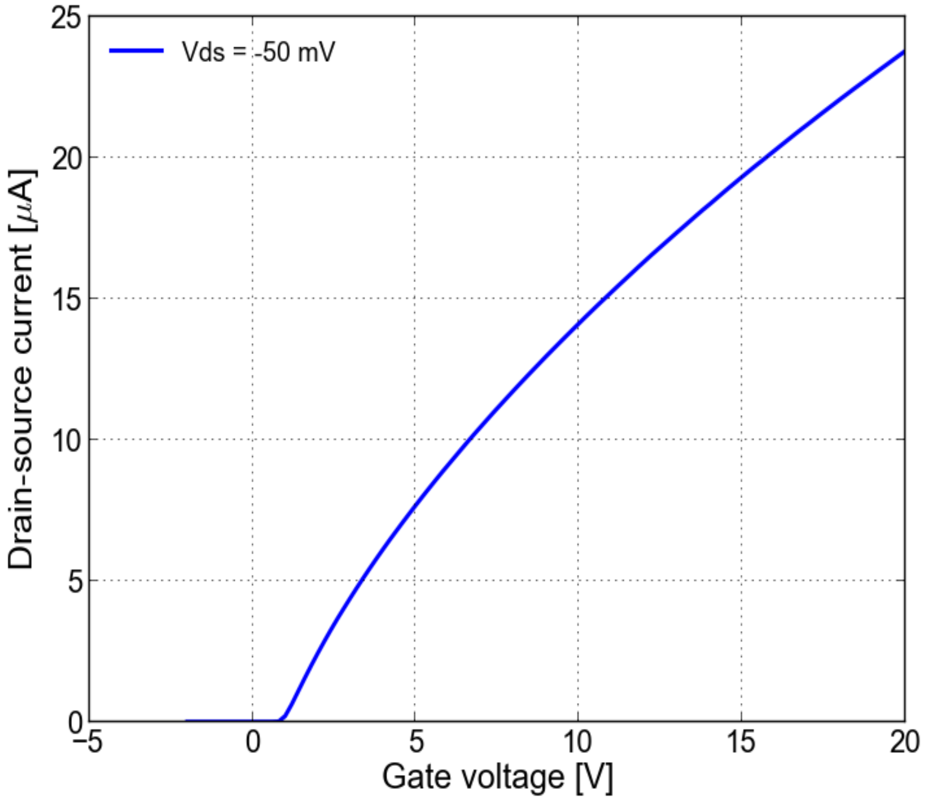


Surface resistivity: MOSFET

- **Circular pMOSFET from SINTEF (AGIPD design)**
  - **- Insulator: 250 nm SiO_2**
  - **- Passivation: 500 nm SiO_2 + 250 nm Si_3N_4 rings**
  - **- 45 µm wide passivation layer between source-gate and gate-drain**
  - **- n-type doping: ≈ $5 \cdot 10^{11}$ cm^{-3}**
  - **- Non-irradiated**
  - **- Crystal orientation: <100>**



1. I_{ds} (V_{gate}) calibration (V_{ds} = - 50 mV)

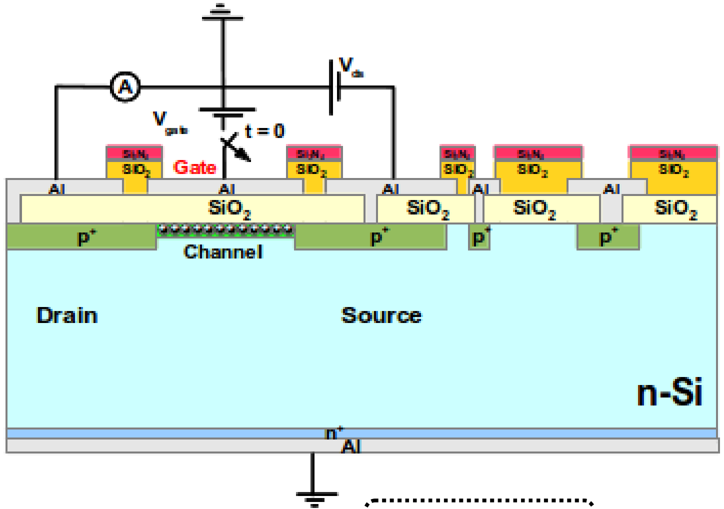


Surface resistivity: MOSFET

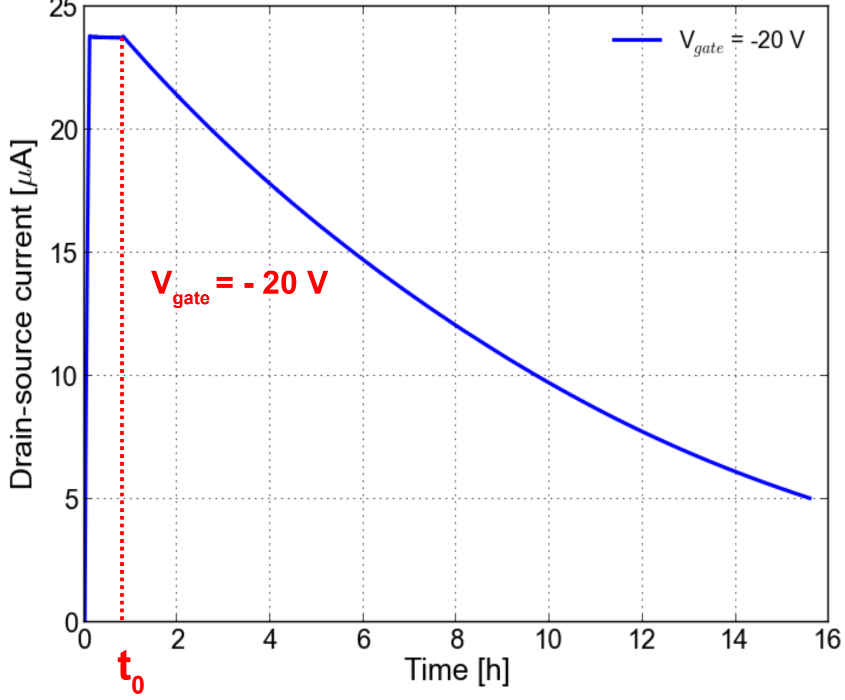
2. Bias V_{gate} to an initial gate voltage V_{ini} , then disconnect the gate probe and measure I_{ds} (t)

- Example: V_{ini} = - 20 V and RH = 50 % at 20 °C

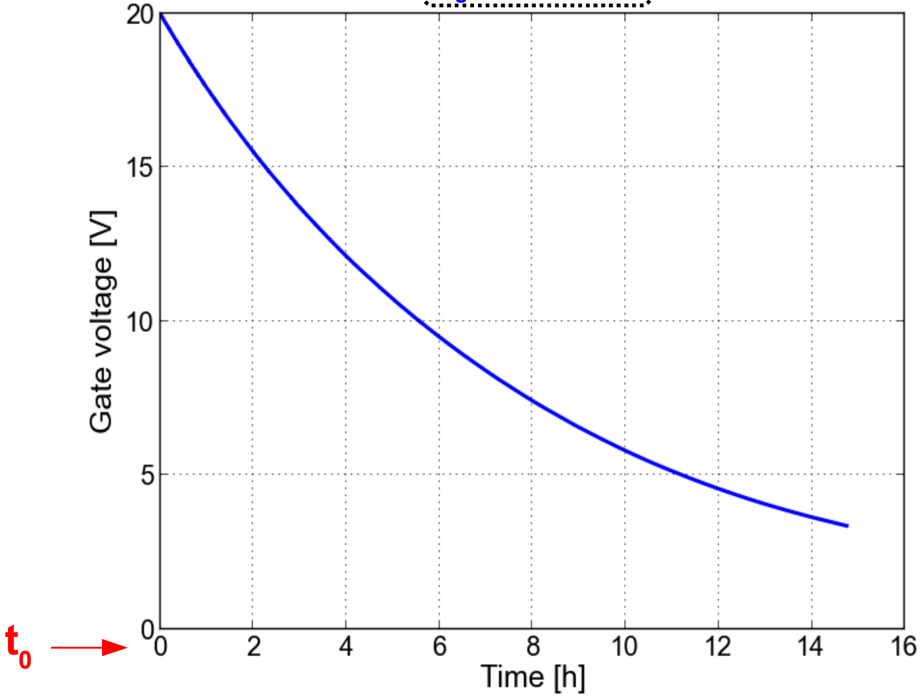
3. For each I_{ds} data point in I_{ds} (t) calculate the corresponding V_{gate} value by interpolating the drain-source current from the I_{ds} (V_{gate})



I_{ds} vs Time



V_{gate} vs Time



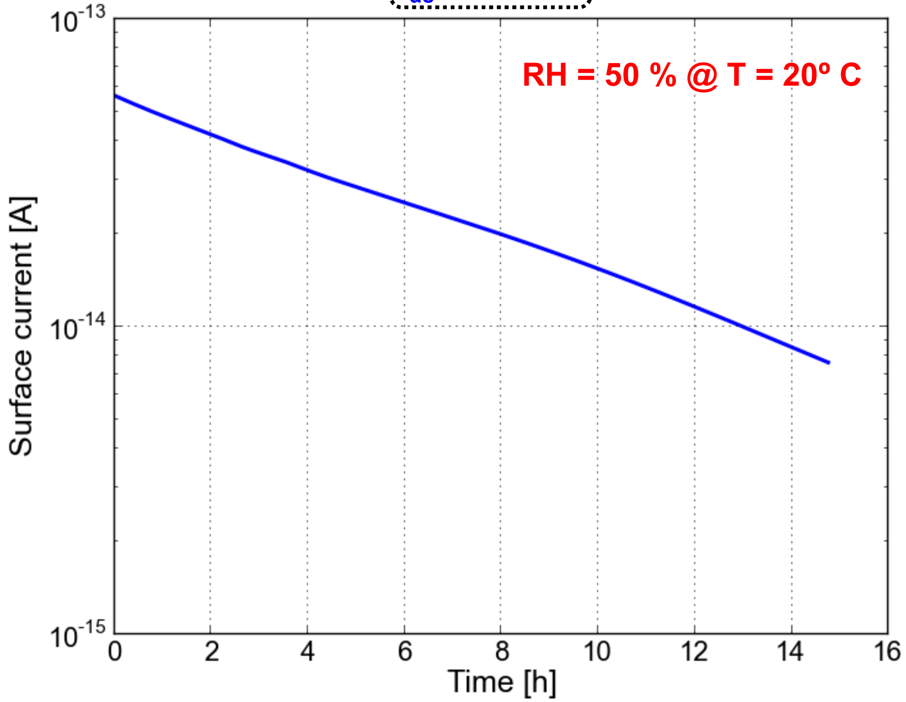
Surface resistivity: MOSFET

4. Calculate I_{surf} (t) = $C_{gate} \cdot dV_{gate}/dt$

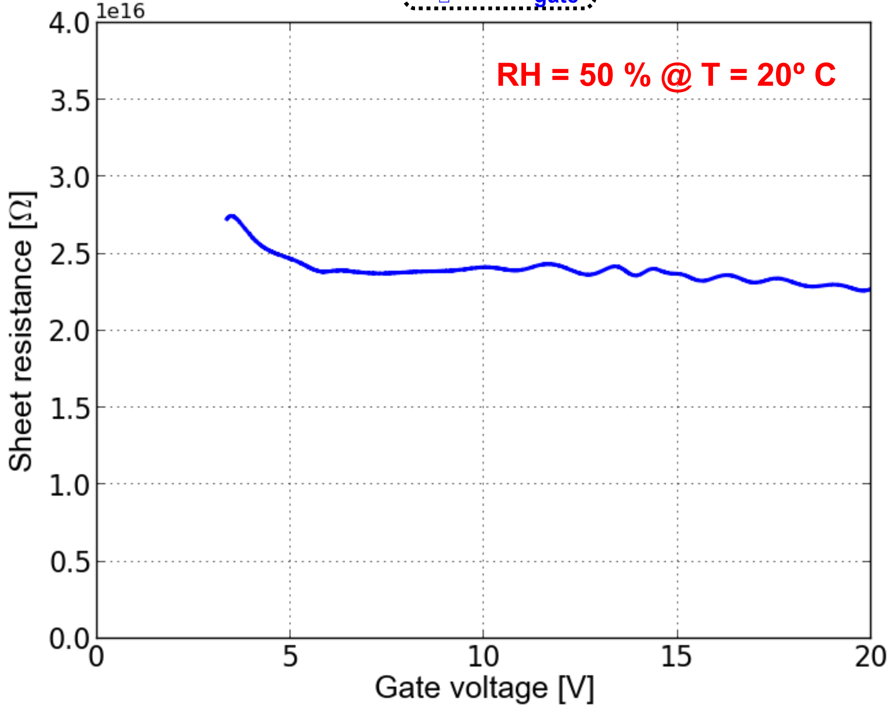
- Determine $R_{surf} = V_{gate}/I_{surf}$

5. Calculate the sheet resistance $R_\square$

I_{ds} vs Time



$R_\square$ vs V_{gate}

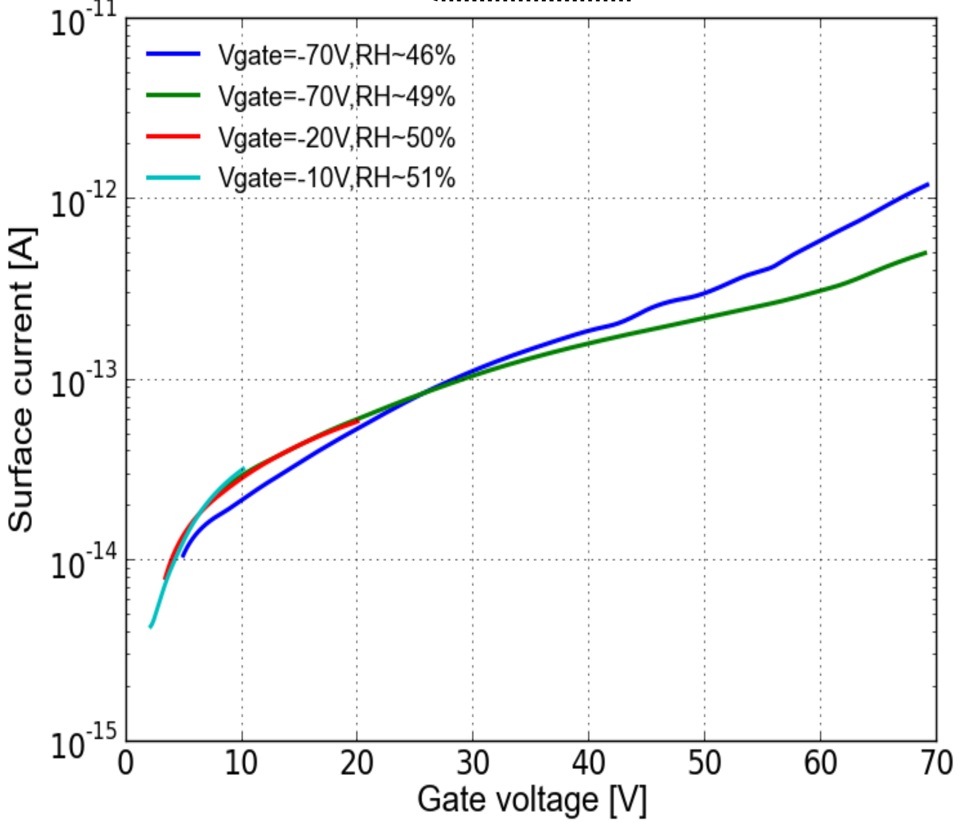


Surface resistivity has ohmic behavior. Extrapolating from simulation p.2: Steady-state reached after 4 days for $R_\square$ → very long time constants.

Surface resistivity: MOSFET

- **Determination of surface current vs. gate voltage for different initial voltages**

I_{surf} vs V_{gate}



From measurements with V_{ini} = - 10 V and V_{ini} = - 70 V no dependence on the initial gate voltage was found, if there are no variations on humidity.

Surface resistivity: Summary

- **Surface resistance $R_\square$:**

  - ohmic characteristics (independent of voltage)

  - strong dependence on humidity (x50 for RH 46 % → 30 %)

  - typical values at RH = 50 % order (10^{16})

  → time to reach steady state conditions in strip sensors: days, and even longer in dry atmosphere

  - dependence on technology/insulator-type and temperature still to be studied

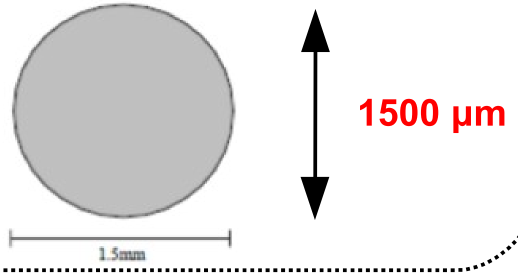
Next:

- **N_{ox} vs. electric field - time – surface damage**

N_{ox}: Field-enhanced charge injection

- **Determination of oxide-charge density (N_{ox}) using C-V measurements on MOS-C as function of E-field + time**

- **Circular MOS-C from CiS**
  - **- Insulator: 350 nm SiO_2 + 50 nm Si_3N_4**
  - **- Non-irradiated and irradiated to 1 GGy**
  - **- Crystal orientation: <100> and <111>**



- **Bias cycle for the gate voltage V_{gate}**

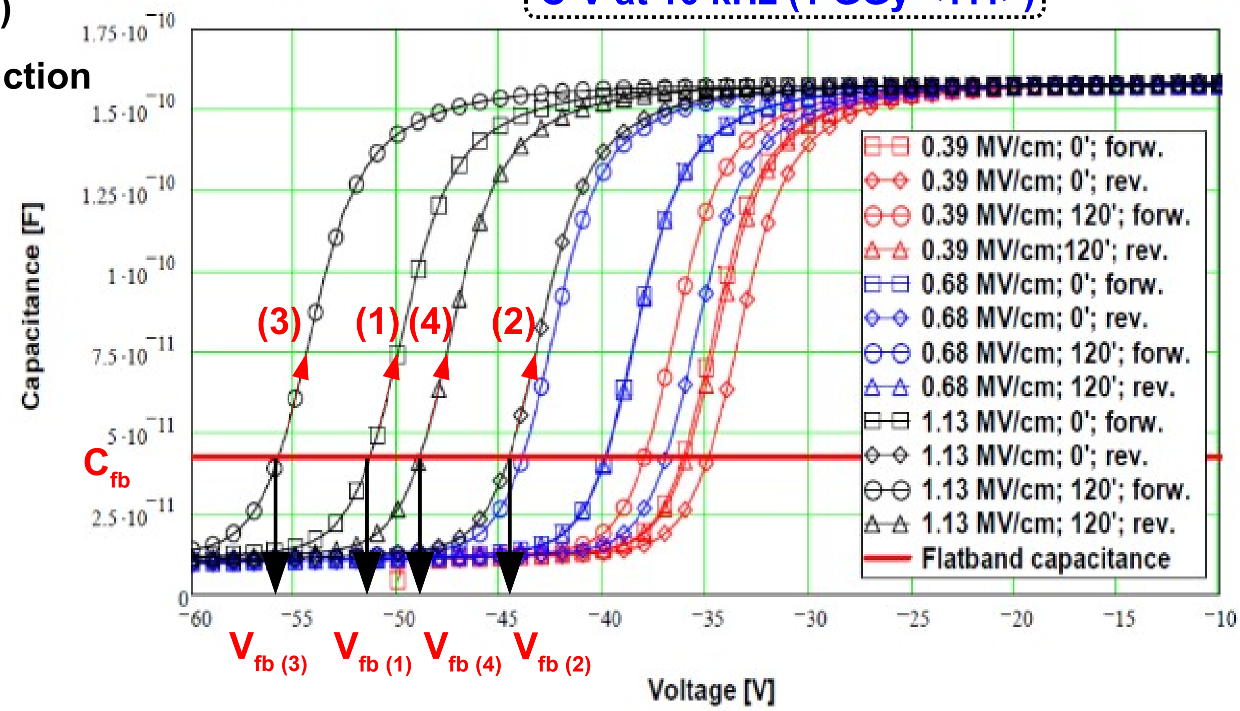
1. Set V_{gate} to V_{ini} in inversion

2. Remain at V_{ini} for the time interval t_{bias}

3. Ramp V_{gate} from inversion to accumulation (forward ramp) and back to V_{ini} (reverse ramp)

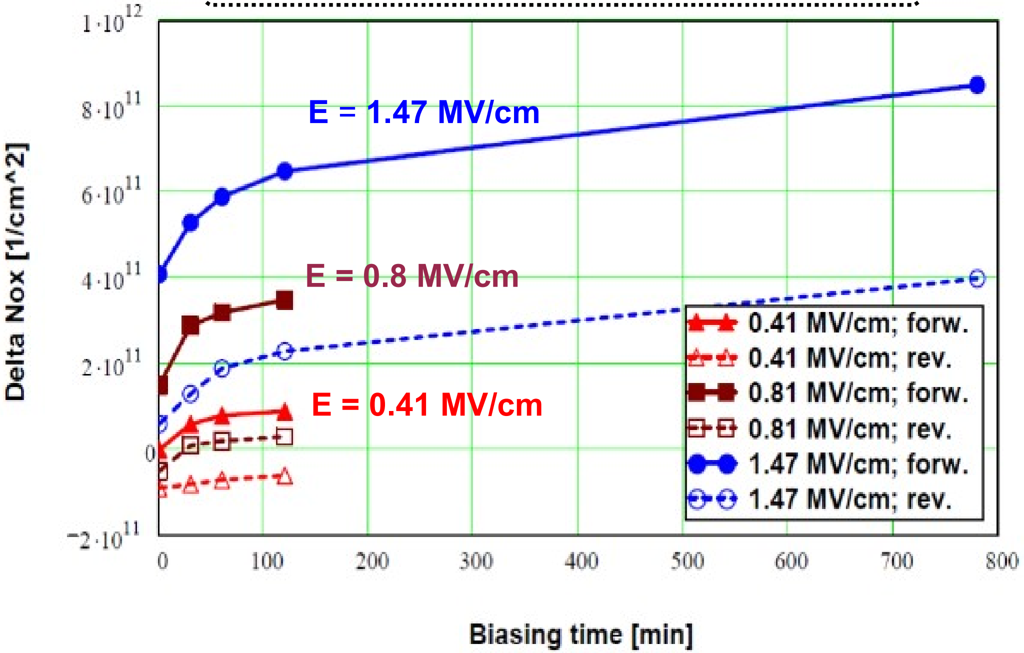
4. Start new cycle with different t_{bias}

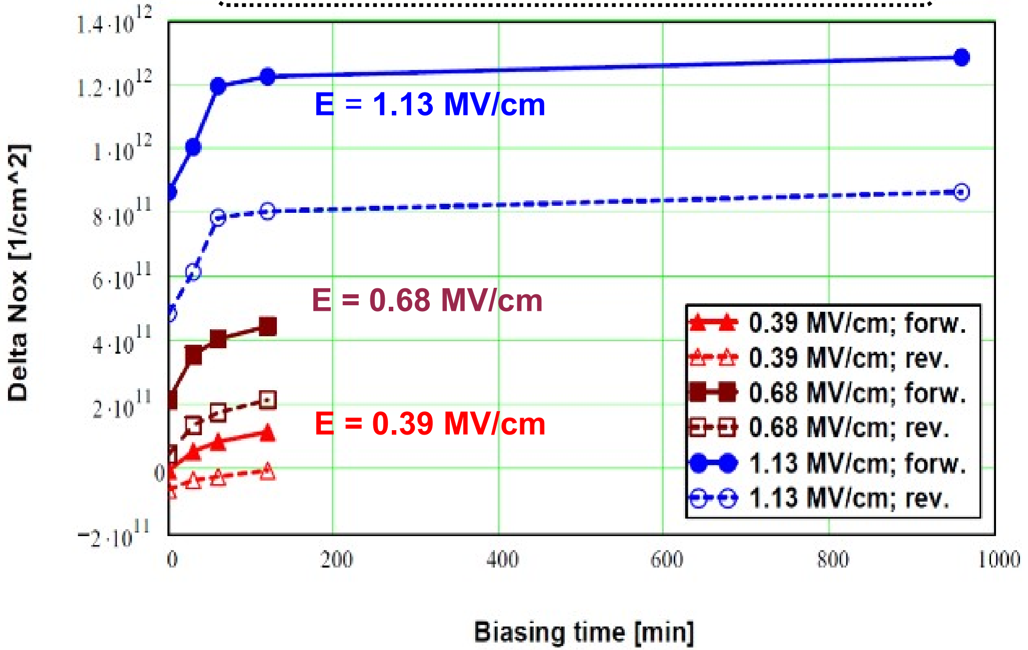
C-V at 10 kHz (1 GGy <111>)



- **For E = 1.13 MV/cm**
  (1): t_{bias} = 0' forw.: initial V_{fb} → N_{ox}^0
  (2): t_{bias} = 0' rev.: $\Delta V_{fb} < 0$ → $\Delta N_{ox} < 0$ discharge of states close to the interface
  (3): t_{bias} = 120' forw.: $\Delta V_{fb} > 0$ → $\Delta N_{ox} > 0$ field-enhanced charge injection
- **(4): t_{bias} = 120' rev.: decrease of ΔV_{fb} → discharge of states close to the interface**

N_{ox}: Field-enhanced charge injection


ΔN_{ox} from C-V at 10 kHz (1 GGy, <100>)


ΔN_{ox} from C-V at 10 kHz (1 GGy, <111>)

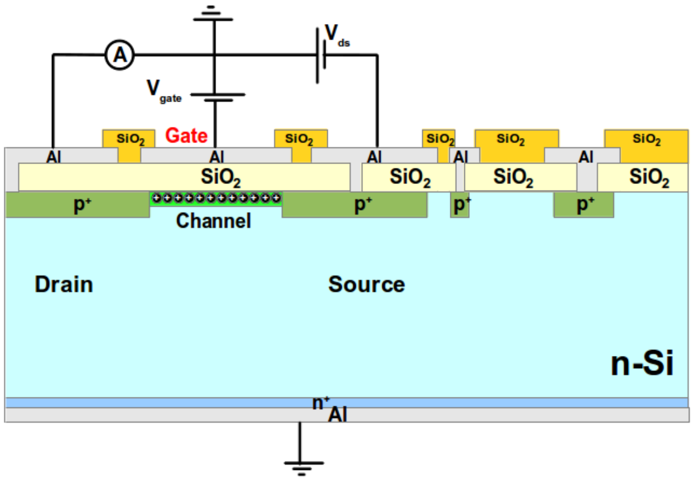
- $N_{ox} = C_{ox} \cdot (-V_{fb} + \Phi_{ms})/(q_0 \cdot A_g)$
- N^0_{ox} value of N_{ox} determined from forward C-V curve at lowest V_{ini} and for t_{bias} = 0 min
- $\Delta N_{ox} = N_{ox} - N^0_{ox}$
- $E \approx |V_{gate} - V_{fb}|/d_{ox}$

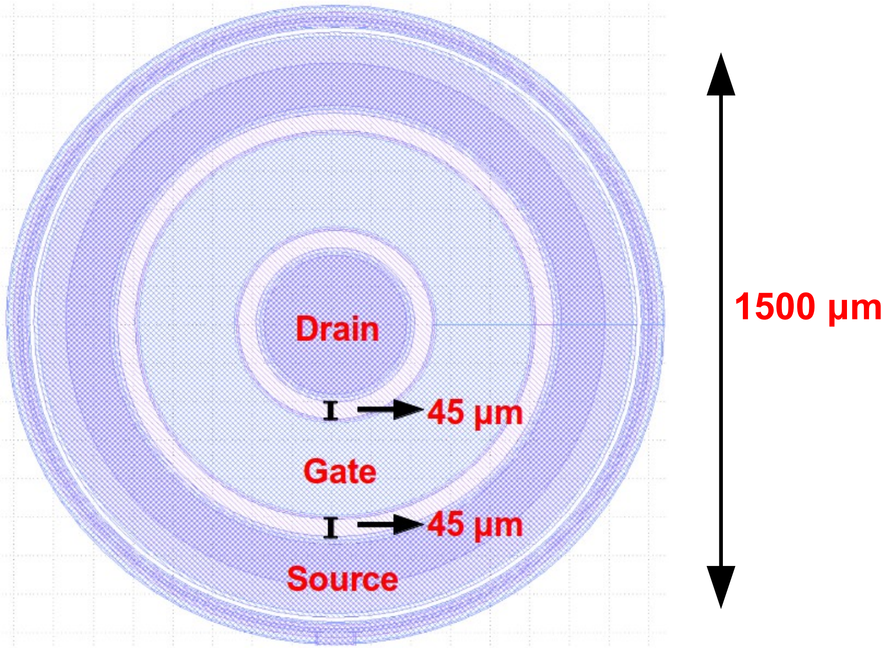
Field-ehanced charge injection observed

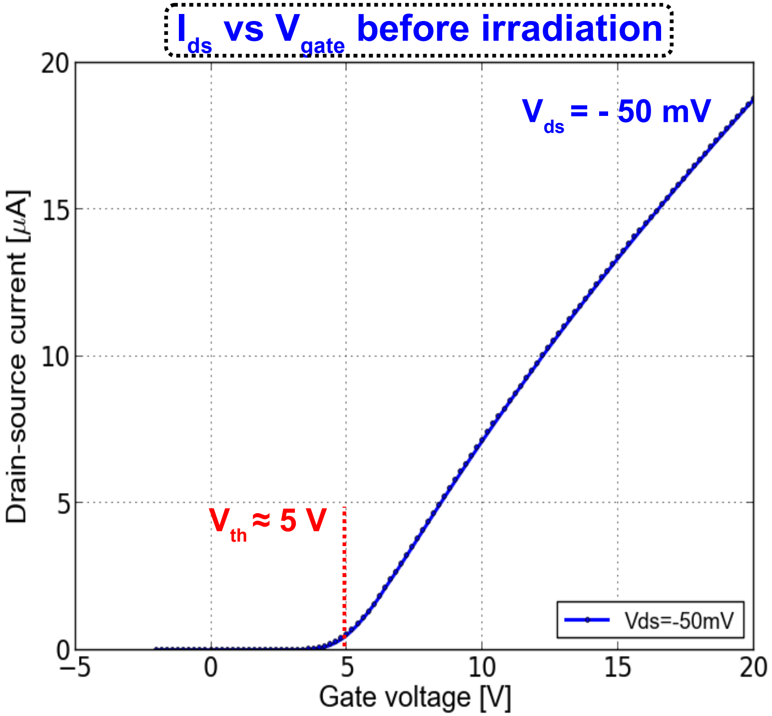
- N_{ox} increases with t_{bias} and saturation values are reached after about 120 min
- For non-irradiated MOS-Cs the effects are at most 20 % of the initial N^0_{ox}
- For irradiated MOS-Cs the effects are as high as 50 % of the initial N^0_{ox}
- Effects are always bigger for <111> MOS-Cs compared to <100> MOS-Cs
- Difference N_{ox} for forward and reverse ramps → Discharge near-surface states in accumulation

Determination of N_{ox}: MOSFET

- Determination of oxide-charge density (N_{ox}) using I_{ds} (V_{gate}) measurements on pMOSFET as a function of X-ray irradiation
- Circular pMOSFET from Canberra (AGIPD design)
  - Insulator: 250 nm SiO_2
  - n-type doping: ≈ $6\cdot10^{11}$ cm^{-3}
  - Crystal orientation: <111>
- Operation of the test device for constant V_{ds}







Selected value of drain-source voltage in nonsaturation region V_{ds} = - 50 mV.

Measurement cycle with the MOSFET

- **Establish of a measurement cycle to measure the threshold voltage shift due to field-enhanced injection of positive charges at the Si-SiO$_2$ interface**

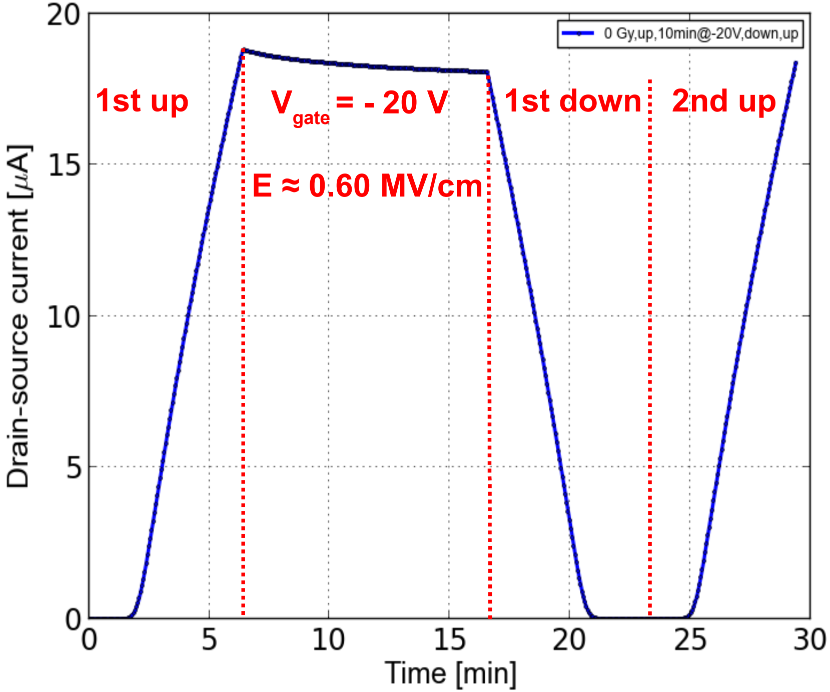
  - 1st up: I_{ds} vs V_{gate} from accumulation (2 V) to strong inversion (- 20 V)

  - Bias the V_{gate} @ - 20 V for 10 min and record the I_{ds}

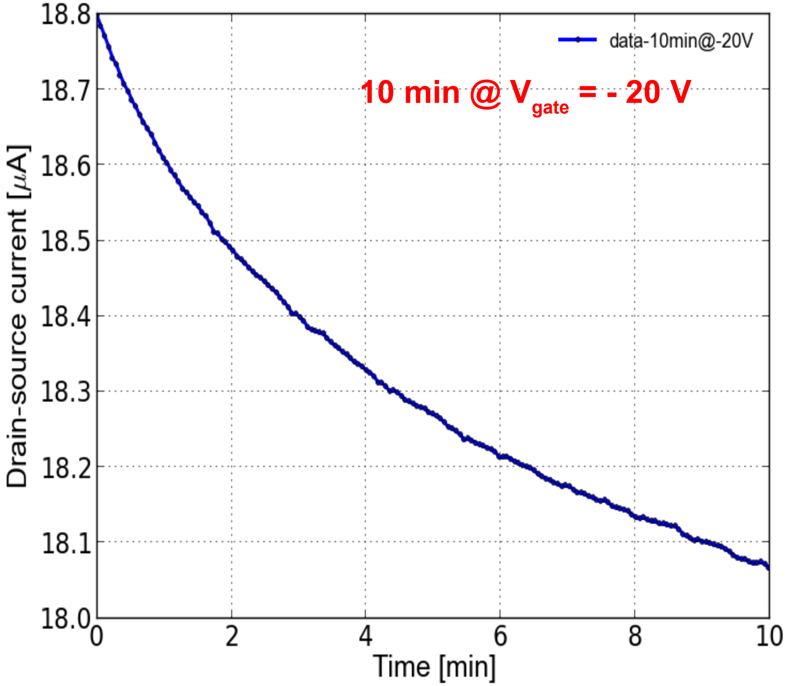
  - 1st down: I_{ds} vs V_{gate} from strong inversion (- 20 V) to accumulation (2 V)

  - 2nd up: I_{ds} vs V_{gate} from accumulation (2 V) to strong inversion (- 20 V)

I_{ds} vs Time before irradiation-cycle



I_{ds} vs Time before irradiation

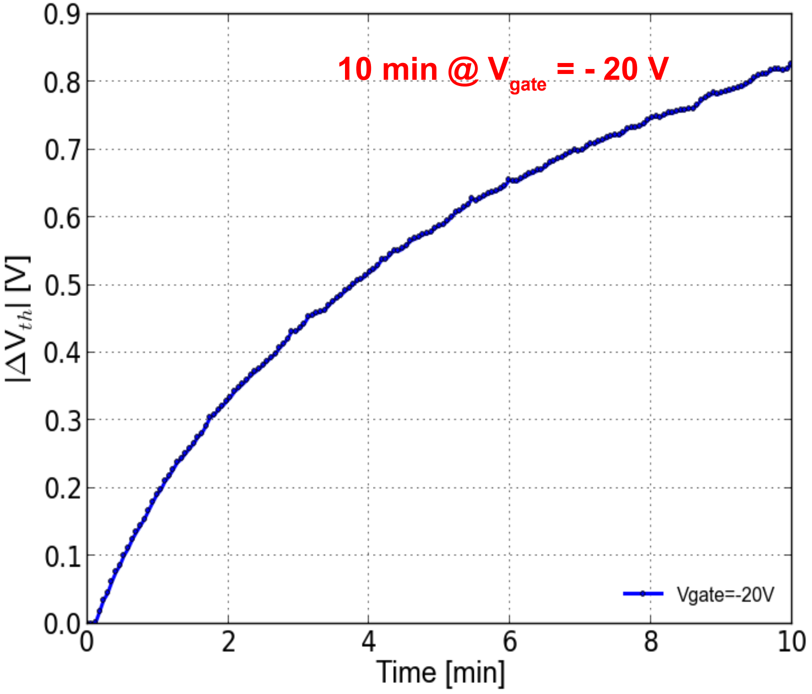


From the decrease of I_{ds} (t) for constant V_{gate} we obtain V_{th} (t) and ΔN_{ox} (t).
Measurement is also possible during irradiation.

N_{ox}: Field-enhanced charge injection

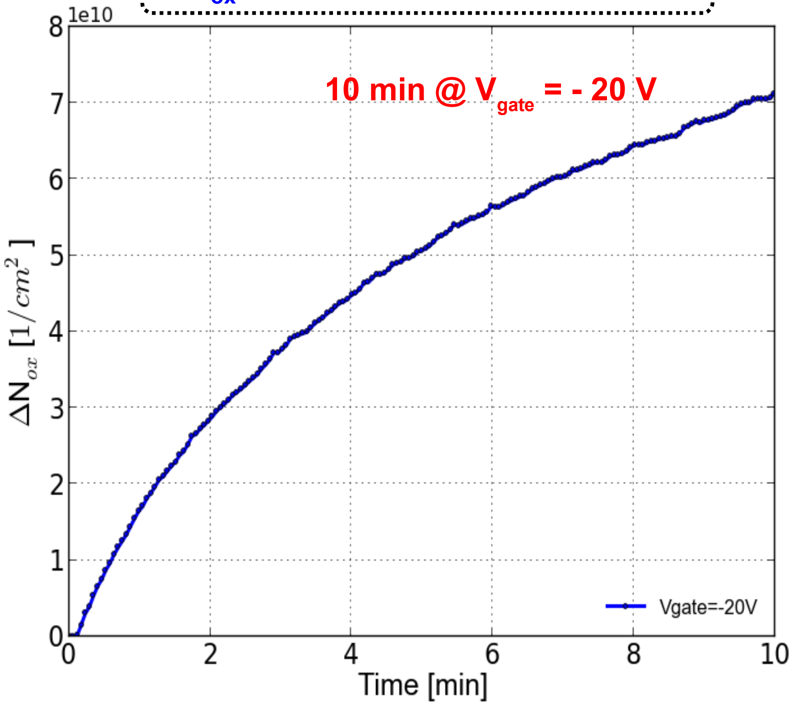
- Use 1st up curve to relate change of I_{ds} to V_{th}

ΔV_{th} vs Time before irradiation



10 min @ V_{gate} = - 20 V

ΔN_{ox} vs Time before irradiation



10 min @ V_{gate} = - 20 V

- **Assume the threshold voltage shift is equal to the flatband voltage shift** $\Delta V_{th} = \Delta V_{fb}$
- **The positive charge carrier injection at the Si-SiO$_2$ interface is calculated from** $\Delta N_{ox} = \frac{C_{ox} \cdot \Delta V_{fb}}{q_0 \cdot A_{gate}}$

Monitoring of the charge carrier injection during the bias stressing at V_{gate} = - 20 V for 10 min.

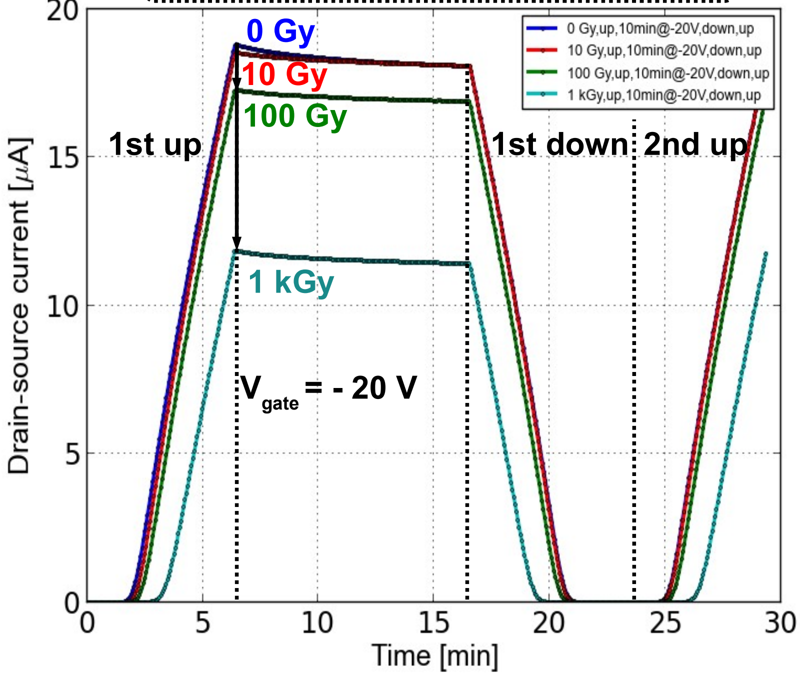
N_{ox}: X-ray irradiation

- Apply the measurement cycle to measure the threshold voltage shift due to field-enhanced injection of positive charges at the Si-SiO_2 interface as function of X-ray irradiation

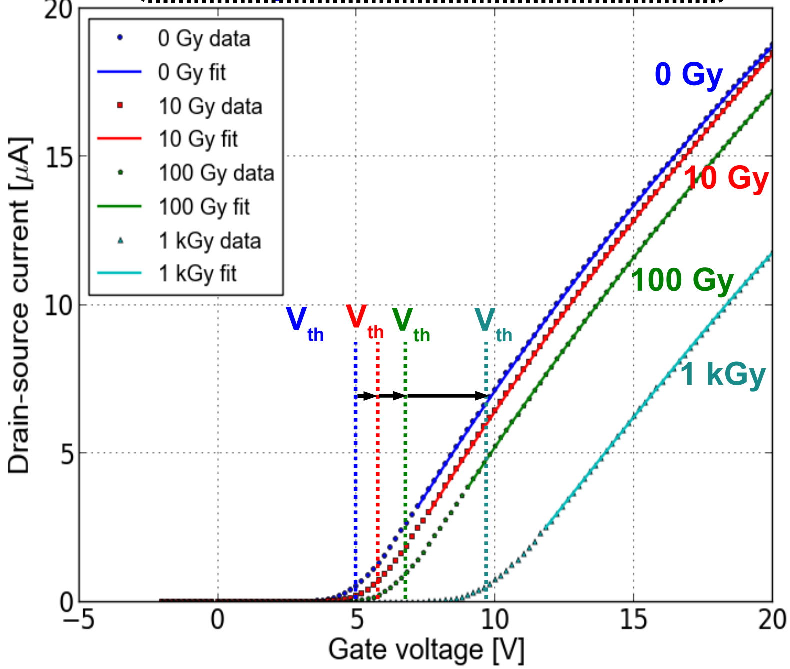
  - Measurement immediately after irradiation

  - Bias V_{gate} = 0 V during irradiation and V_{ds} = - 50 mV

I_{ds} vs Time after irradiation-cycle



I_{ds} vs V_{gate} after irradiation-1st up



Significant increase ~ 100% of N_{ox} for irradiation dose up to 1 kGy.

Dose [Gy]	V_{th}	V_{fb}	N_{ox} [10^{11} cm^{-2}]	N_{ox} (Dose) – N_{ox} (0 Gy) [10^{11} cm^{-2}]
0	5.0	4.8	3.8	0
10	5.6	5.4	4.3	0.5
100	6.4	6.1	4.9	1.1
1 k	9.7	9.4	7.8	4.0

Conclusions and Outlook

- The performance of segmented Si-sensors is influenced by the conditions at the sensor surface and at the Si-SiO_2 interface
- Time constants for reaching steady-state conditions as long as weeks have been observed
- So far hardly any systematic studies have been made

- We have established methods to measure:
  1. The surface resistivity
  2. The charge density at and close to Si-SiO_2 interface (N_{ox}) as functions of electric field and biasing time

- Next:
  1. Implement results in TCAD simulations
  2. Extend measurements to different humidity and dose values
  3. Check dependence on technology

Suggestions are welcome.
Thank you for your attention.

Back up

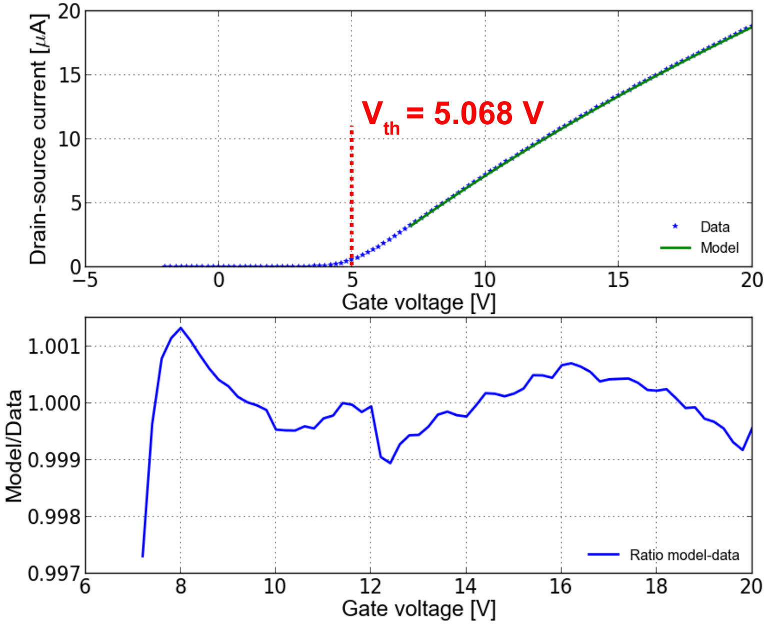
Mobility parameterization model and data fit

- **The mobility of holes in the inversion layer is not constant as function of the E-field at the interface**

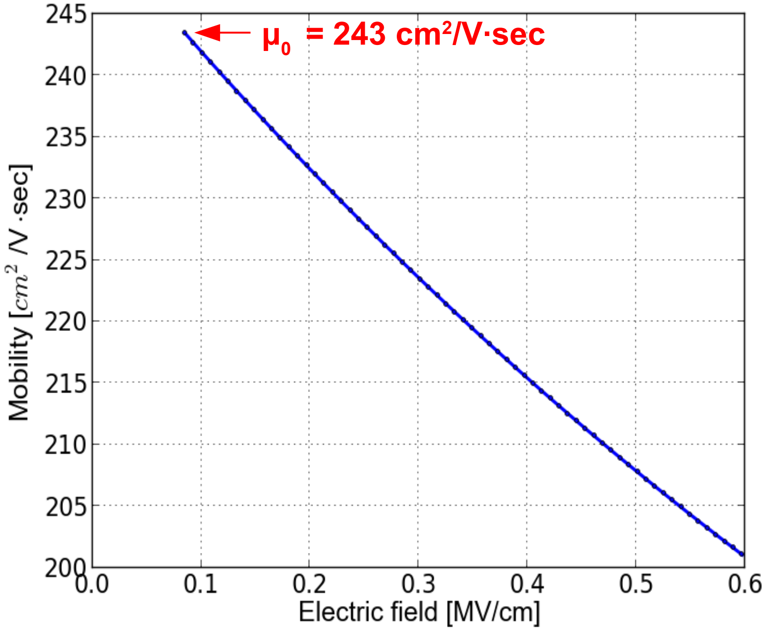
  - Non linear behavior of the drain-source current vs gate voltage

  - Exponential decrease of the mobility as function of the E-field

I_{ds} vs V_{gate} before irradiation



μ_p vs E before irradiation



- $$I_{ds} = \mu_p \frac{C_{ox}}{A_{gate}} \frac{W}{L} [(V_{gate} - V_{th})V_{ds} - \frac{1}{2}V_{ds}^2]$$
- $$I_{ds} = \mu_p \frac{C_{ox}}{A_{gate}} \frac{W}{L} V_{ds}(V_{gate} - V_0)$$
- $$V_0 = V_{th} + \frac{1}{2}V_{ds}$$
- $$\mu_p = \mu_0[(1-\beta)e^{-\gamma(V_{gate}-V_0)} + \beta]$$
- $$E = \frac{|V_{gate} - V_{th}|}{d_{ox}}$$
- $$V_{th} = V_{fb} + 2\psi_b + \frac{\sqrt{2\epsilon_{Si}\epsilon_0 q N_d (2\psi_b)}}{\frac{C_{ox}}{A_{gate}}}$$

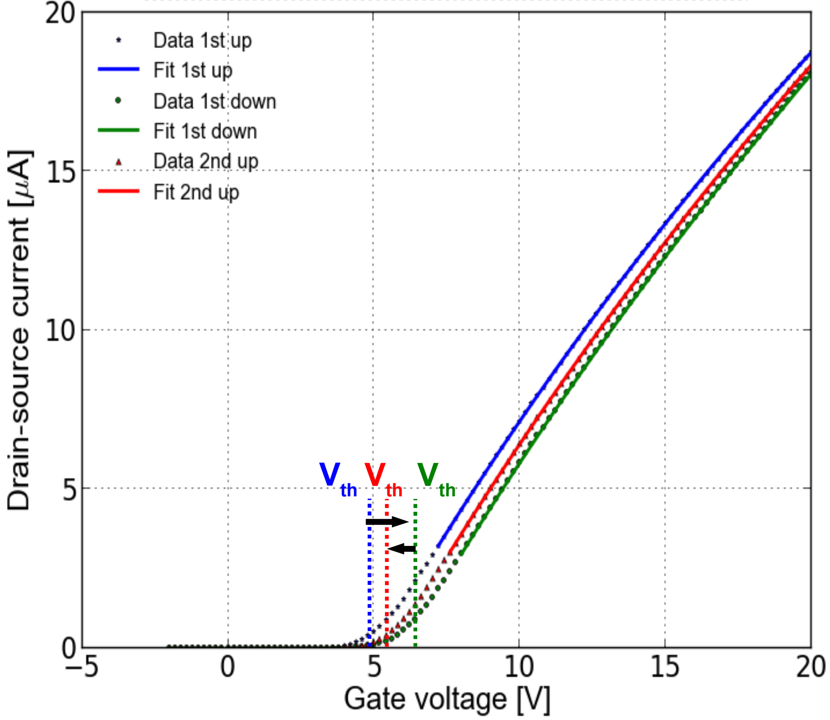
Reliable V_{th} extraction from the parameterization model fit to the data.

N_{ox}: Field-enhanced charge injection

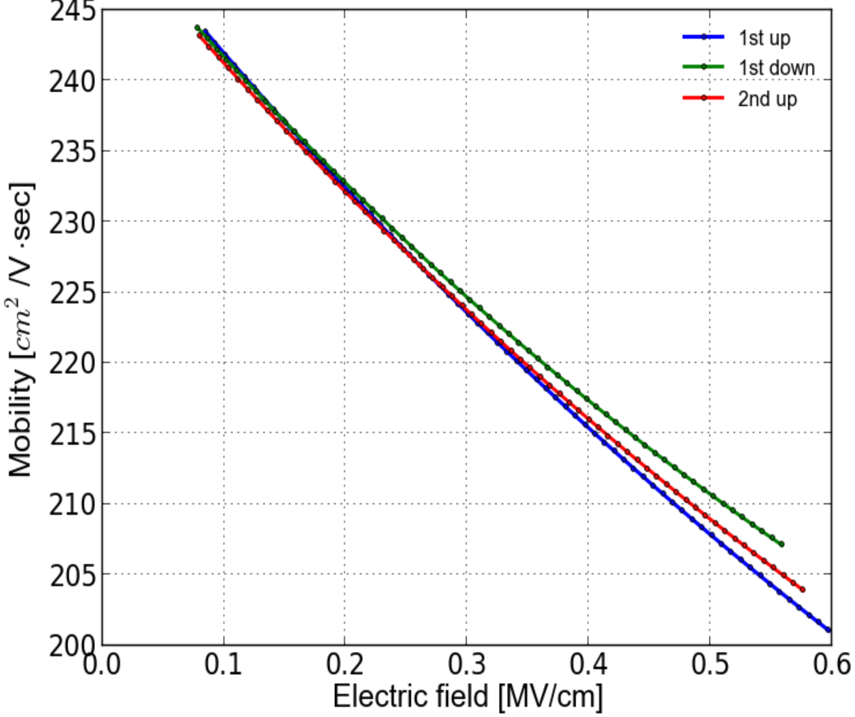
- **Determination of the oxide-charge density (N_{ox}) using the I_{ds} (V_{gate}) curve before irradiation**

  - V_{th} extraction from the model fit to the measurement cycle

  - Calculation of V_{fb} from the V_{th}



I_{ds} vs V_{gate} before irradiation-cycle



μ_p vs E before irradiation-cycle

- **$N_{ox} = C_{ox} \cdot (-V_{fb} + \Phi_{ms})/(q_0 \cdot A_g)$**

0 Gy	V_{th} [V]	V_{fb} [V]	N_{ox} [10^{11} cm^{-2}]
1st up	5.0	4.8	3.8
1st down	6.0	5.8	4.6
2nd up	5.6	5.3	4.2

N_{ox} increases after bias stressing at V_{gate} = - 20 V for 10 min.